Transactions

AMERICAN FOUNDRYMEN'S ASSOCIATION

Contents

East Engin. Library

Application of Controlled Directional Solidification to Large Steel Castings, *by J. A. Duma and S. W. Brinson* 225

Heat Treatment of Malleable Iron, *by R. J. Cowan*..... 283

Effects of Sulphur on Properties of Electric Furnace Cast Iron, *by Fulton Holtby and R. L. Dowdell*..... 303

Crucible Melting with Modern Gas Burners, *by F. L. Wolf* 347

Measuring the Tendency of Some Cast Irons to Seize Under Sliding Friction, *by A. H. Dierker, Bernard Fried and H. H. Dawson*..... 355

Coatings for Wood Patterns, *by F. C. Cech and V. J. Sedlon* 369

Sand Affects Physical Properties of Gray Iron, *by H. W. Dietert and E. E. Woodliff*..... 393

The Damping Capacity, Endurance, Electric and Thermal Conductivities of Some Gray Irons, *by C. H. Lorig and V. H. Schnee*..... 425

VOL. XLVIII DECEMBER, 1940 NO. 2

TRANSACTIONS

AMERICAN FOUNDRYMEN'S ASSOCIATION
INCORPORATED

Published and copyrighted by the American Foundrymen's Association, Inc., 222 West Adams Street, Chicago, Illinois

Entered as second class matter September 9, 1938 at the postoffice at Chicago, Illinois, under the Act of March 3, 1879

Issued Quarterly

Subscription Price: Members: $4.00 per year; $1.00 per copy

Subscription Price: Non-Members: $15.00 per year; $4.00 per copy

VOL. XLVIII DECEMBER, 1940 NO. 2

A.F.A. Organization and Personnel — 1940-41

Officers and Staff

**President*, L. N. Shannon, Stockham Pipe Fittings Co., Birmingham, Ala.

**Vice President*, H. S. Simpson, National Engineering Co., Chicago, Ill.

**Executive Vice President*, C. E. Hoyt.[1]

Secretary, R. E. Kennedy.[1]

Treasurer, E. O. Jones.[1]

Technical Secretary, N. F. Hindle.[1]

Manager of Exhibits, C. E. Hoyt.[1]

Director of Safety and Hygiene Section, E. O. Jones.[1]

Assistant Secretary-Treasurer, J. Reininga.[1]

Board of Directors

Terms Expire 1941

*H. Bornstein, Deere & Co., Moline, Ill.

*W. H. Doerfner, Saginaw Malleable Iron Div., General Motors Corp., Saginaw, Mich.

H. S. Hersey, The C. O. Bartlett & Snow Co., Cleveland, Ohio.

G. A. Seyler, The Lunkenheimer Co., Cincinnati, Ohio.

A. Walcher, American Steel Foundries, Chicago, Ill.

Terms Expire 1942

W. B. Coleman, W. B. Coleman Co., Philadelphia, Pa.

C. R. Culling, Carondelet Foundry Co., St. Louis, Mo.

Otto A. Pfaff, American Foundry Equipment Co., Mishawaka, Ind.

Marshall Post, Birdsboro Steel Foundry & Machine Co., Birdsboro, Pa.

Fred J. Walls, International Nickel Co., Detroit, Mich.

Terms Expire 1943

G. W. Cannon, Campbell Wyant & Cannon Foundry Co., Muskegon, Mich.

*B. D. Claffey, General Malleable Corp., Waukesha, Wis.

Harold J. Roast, Canadian Bronze Co., Ltd., Montreal, Canada.

L. P. Robinson, Werner G. Smith Co., Cleveland, Ohio.

*H. S. Washburn, Plainville Casting Co., Plainville, Conn.

* Member Executive Committee.
1 Association Office, 222 West Adams St., Chicago, Ill.

Application of Controlled Directional Solidification to Large Steel Castings†

By J. A. Duma* and S. W. Brinson**, Portsmouth, Va.

Abstract

A successful foundry technique has been developed by the Norfolk Navy Yard for the production of large and intricately shaped castings. The success of this technique has been achieved by (1) the use of miniature models for a critical study of the proposed design prior to the making of the final patterns; (2) the foundry's insistence on the application of the principles governing directional solidification; (3) the practice of relieving molds and cores mechanically after pouring; (4) to the use of synthetically bonded silica sand mixes in mold construction; (5) to the high quality of the steel used and (6) to the constant and widespread use of gamma-ray examination of the internal structure of all critical sections. Brief comments are made on all these practices mentioned. In this report, actual cases are presented which illustrate the various ways in which the direction of solidification is being controlled successfully on large work. Anchor shanks and anchor crowns, globe valve bodies, main and intermediate struts, turbine casings, throttle valve bodies and turret roller track sections are some of the examples of castings described.

Part 1—Introduction

1. The total and partial reversal methods of applying controlled, directional solidification to castings are fairly well known to foundrymen. Unfortunately, the reversal systems are not applicable to all manner and size of castings, their range of usefulness being limited to comparatively small and medium-size structures. Huge molds, containing from 10,000 to 30,000 lb. of liquid

* Asst. Metallurgist, Norfolk Navy Yard.
** Master Molder, Norfolk Navy Yard.
† Published by permission of the Navy Department.
Note: This paper was presented at a Steel Session of the 44th A.F.A. Convention, May 10, 1940, Chicago, Ill.

steel, cannot be craned for reversing with the same facile promptness and safety as molds containing one-tenth that amount of metal. This does not by any means preclude the use of the principle of controlled, directional, solidification on large castings. Favorable temperature gradients can be imposed upon them, but in a manner distinctly different from that used in the reversal systems. In the following pages, actual cases will be presented illustrating the various ways in which the direction of solidification is being successfully controlled on large work. The castings whose manufacture will be described are anchor shanks and anchor crowns, globe-valve bodies, main and intermediate struts, turbine casings, throttle-valve bodies, and turret-roller track sections.

2. Controlled, directional, solidification, while admittedly indispensable for the procurement of solidity in castings, per se, is unable to achieve flawlessness. The degree of excellence attained in cast structures is further dependent upon their design, the manner of metal handling and molding technique. Perfectly sound castings are rare. Therefore, for a casting to be as nearly perfect as possible, the best effort and the highest skill of the designer, melter, molder, and patternmaker must be incorporated into it.

3. An eminently successful foundry technique has been evolved at the Norfolk Navy Yard for the founding of large and intricately shaped castings, notably turbine casings. The high degree of success achieved is due principally to: (1) the employment of miniature models for a critical study of the proposed design prior to the making of the final patterns; (2) the foundry's insistence on the application, to the fullest extent practically possible, of the principles governing directional solidification; (3) the practice of relieving molds and cores mechanically after pouring, (4) to the use of synthetically bonded silica sand mixes in mold construction, (5) to the high quality of the steel used; and (6) to the constant and widespread use of gamma-ray examination of the internal structure of all critical sections. The wealth of technical information generously supplied to the Navy Yard by the Naval Research Laboratory likewise contributed to the success attained.

Design

4. Commenting very briefly on each of the foregoing practices, and in the same order, a preliminary study of subsize models invariably leads to constructive changes in the original design.

Complicated appurtenances, which interrupt the symmetry of the main body, are either left off, to be cast separately, or they are left intact, depending on whether or not they interfere with the proper feeding of other sections, and whether or not they themselves are amenable to feeding. All corners are properly radiused; sharp re-entrant angles are suitably filleted; thin and thick sections are run into each other gradually; sudden dips and sharp changes in the surface contour are straightened out; joining of other sections is checked carefully for potential hot spots; and where possible the entire transverse section is heavily tapered or padded from the bottom to the feeding-heads, thus simulating the big-end-up mold design of the steel mills. The placement of feed-heads and the manner of core anchorage are also worked out. The result usually is a design that is castable with the minimum amount of potential defects.

Advantages of Models

5. Models are self-paying. Costing approximately 2 per cent of the total founding cost of a casting, they affect savings of equivalent or greater magnitude. By referring to the model, the making of the pattern, core boxes, and mold is greatly expedited. Chipping of exterior padding is also hastened.

6. Controlled, directional, solidification, when properly applied, is generally productive of a uniformly solid casting, free from nearly all the shrinkage defects which are wont to afflict the conventionally made product, *i.e.*, micro-pipe, cokey texture, pronounced center-line weakness, gross shrinkage cavities, and internal hot tears. This topic is dealt with at greater length in following sections of the paper.

Mold Relieving

7. Mold relieving is to a casting's solid contraction what directional solidification is to its fluid contraction. Solid contraction is a problem which involves the questions of hot shortness of metal and deformability of molds. Relieving of molds after pouring helps obviate external hot tears. For a casting to tear, two conditions are necessary, namely: high temperature (2300-2550°F.) and high hindered contraction stresses (800-2500 lb. per sq. in.)[1]. Since, of the two, the latter is controllable and therefore avoidable, the cure for them is self-evident. To prevent the stresses opposing contraction from building-up to magnitudes exceeding the strength of the

[1] Superior numbers refer to bibliography at end of paper.

Table 1 *(See Appendix 1)*

STEEL MOLDING AND CORE SAND MIXES[1]

PART 1 — STEEL MOLDING SANDS

	Composition					Drying Treatment				Physical Properties				
	Sand[2]											Compression,	Shear,	
Mix No.	Kind	Amt., lb.	Bentonite[3], lb.	Moisture, per cent	Surface[4] Treatment	Medium	Temp., °F.	Time, hr.	Aging[5] hr.	Skin Dried	Permeability	lb. per sq. in.	lb. per sq. in.	Moisture, per cent
1a					As-is	...	...	...	...	...	260.0	11.0	3.8	3.50
1b					As-is	Oven	225	1	...	...	325.0	45.7	14.1	...
1c					Sprayed[6]	Air	Room	24	...	Yes	295.0	37.3	9.2	0.70
1d	No. 50	500	45	3.5	Sprayed	Air	Room	60	...	Yes	305.0	45.7	12.0	0.35
1e					Sprayed	Air	Room	60	...	No	305.0	35.1	10.0	1.20
1f					As-is	Air	Room	60	...	No	320.0	25.2	8.5	0.90
1g					As-is	Air	Room	120	...	No	320.0	19.4	7.5	0.70
1h					Sprayed	Air	Room	120	...	Yes	290.0	47.1	12.0	0.50
2a					As-is	...	...	...	...	...	127.5	9.9	3.5	5.00
2b					As-is	Oven	225	1	...	...	165.0	193.5	32.0	...
2c					Washed	Oven	225	1	...	...	50.0	194.0	35.0	...
2d					As-is	Oven	600	1	...	...	179.5	194.5	30.6	...
2e	No. 50	350	18	5.0	Washed	Oven	600	1	...	...	51.7	197.5	32.5	...
2f	No. 95	200			As-is	Oven	600	3	...	...	190.0	164.5	30.3	...
2g					Washed	Oven	600	3	...	...	60.2	173.0	31.1	...
2h					As-is	M. Oven[7]	500	16	...	...	190.0	188.5	32.0	...
2i					Washed	M. Oven	500	16	...	...	73.7	197.0	32.1	...
2j					Washed	M. Oven	500	16	72	...	65.0	68.8	19.8	0.35
2k					Washed	M. Oven	500	16	120	...	70.2	71.0	19.0	0.55
3a					As-is	...	...	...	...	...	260.0	10.0	3.5	5.20
3b					As-is	Oven	225	1	...	...	380.0	194.5	35.0	...
3c	No. 50	500	60	5.2	As-is	M. Oven	475	14	...	...	385.0	194.0	33.0	...
3d					Washed	M. Oven	475	14	...	...	162.0	207.0	39.0	...
3e					Washed	M. Oven	475	14	48	...	167.0	50.6	12.0	...
4a	Heap	...	...	5.0	As-is	...	...	...	...	...	155.0	4.4	1.4	5.00
4b					As-is	Oven	225	1	...	...	200.0	78.6	24.6	...

[1] Specimens and results are according to, and in units of, A.F.A. Standards and methods. All results are the average of at least three individual tests.

[2] The following are the uses and composition of the above sands.

Uses:

Mix No. 1 — For castings of complicated design.
Mix No. 2 — For castings of heavy section and of fairly harmonious design. Also used in large cores.
Mix No. 3 — For the making of the cope of some of the above castings.
Mix No. 4 — For backing up facing mixes Nos. 1 and 2.
Mix No. 5 — For interior cores, where high green strength is required.
Mix No. 6 — For interior and exterior cores, where no green strength is required.

Composition: No.	Name	A.F.A. Fineness No.	Clay, Per Cent	Moisture, Per Cent
50	Cape Henry Silica Sand	40-60	...	3.5
60	White Jersey Silica Sand	60	...	3.7
93	Steel Bond Sand	96.5	20.2	...
..	Steel Heap Sand	52.4	6.8	5.0
..	Used Sandblast Sand	72.7	...	...
..	Bentonite Clay	0.1-5.0 microns		8.0

[3] Bentonite is a natural clay consisting principally of silica and alumina.

[4] In practice, green sand molds are sprayed with molasses water; dry molds are washed with silica wash; sandblast cores are sprayed with linseed oil; oil sand cores are sometimes washed with silica wash. The values given in Table 1 were obtained on specimens sprayed or washed on one side only.

Molasses Water

Composition: Mixed to proportion
3 parts foundry molasses to
50 parts water.
Specific Gravity: 1.009 (60°F.)

Silica Wash

125.0 lb. Silica Flour
4.5 lb. Bentonite Clay
1.5 lb. Cereal Binder
125.0 lb. Water
Sp. Gr. = 1.500

[5] Aging: Time elapsing from the making of the mold to its pouring.

[6] All green sand molds are skin dried with a gas torch before closing.

[7] M. Oven = Mold drying oven.

Part 2 — Core Mixes

Mix No.	Sand Kind	Sand Amt., qt.	Cereal Binder, qt.	Linseed Oil, qt.	Moisture, per cent	Surface[4] Treatment	Baking Time, hr.	Temp., °F.	Exposure[5] to Air, hr.	Physical Properties: Permeability	Tensile Strength, lb. per sq. in.	Transverse Strength, lb.	Flexure, lb.
5a	Blast	120	2	2	7.8	As-is	4	450	...	63.0	159.5	31.8	25.3
5b						Sprayed	4	450	...	63.0	163.5	35.5	27.6
5c						Washed	4	450	...	12.0	151.8	31.5	26.0
5d						Sp'd & W'd	4	450	...	12.0	169.0	38.8	26.8
5e						Sprayed	4	450	120	62.0	164.5	34.7	34.3
5f						As-is	½	600	...	63.0	169.5	35.5	21.5
5g						Sprayed	½	600	...	62.0	154.5	48.3	27.3
5h						As-is	¾	600	...	63.0	109.0	29.8	13.0
5i						Sprayed	¾	600	...	63.0	122.5	21.7	13.5
6a	No. 60	120	..	2	7.3	As-is	⅝	450	...	170.0	125.0	30.0	11.0
7a	No. 60	120	2	2	7.0	As-is	4	450	...	160.0	138.0	30.8	13.1
7b						Sprayed	4	450	...	150.0	166.5	42.0	26.8
7c						Washed	4	450	...	20.0	169.0	37.0	18.8
7d						Sprayed	4	450	120	165.0	133.5	23.5	13.0
7e						As-is	½	600	...	143.3	187.5	22.8	43.5
7f						Sprayed	½	600	...	136.6	194.5	30.5	47.5
7g						As-is	¾	600	...	145.0	163.0	29.3	38.7
7h						Sprayed	¾	600	...	140.0	203.5	36.3	48.8

metal at the above temperatures, mold and core materials must possess, after pouring, immediate and ready collapsibility. Green sand molds exhibit this behavior to a remarkable degree. Mold resistance is lowered still further by mechanical loosening of cope bars and tie rods, by pulling-out and relieving blocks, and by breaking core crabs. Because they permit the casting to contract unobstructedly at both high and low temperatures, all the foregoing operations help save it from failure by hot tearing.

Effects of Sand

8. Sand conditions, too, are responsible for a large proportion of defective castings. Some of the more serious casting defects directly chargeable to sand are blows, pinholes, gas cavities, scabs, buckles, rough surface, drops, cutting, and sand inclusions. Synthetically bonded sand mixes, consisting of washed silica sand, water, and bentonite, are not only simple in composition and inexpensive, but remarkably resistant to damage by molten steel. Ample protection is secured for the solidifying casting against the first three defects by: (1) the absence of organic (gas forming) materials in the mixes; (2) low moisture content; and (3) high permeability. A nice balancing of the various physical properties of these mixes (in practice secured by suitable tempering, ramming, and drying) will safeguard the casting against the remaining defects. The composition and physical properties of the various sand mixes used for making each of the castings described are contained in Table 1.

Melting Technique

9. Melting technique is responsible for two very serious ailments, porosity and low ductility[2]. The former is a disease of unsufficiently deoxidized steel, while the latter is associated with over-reduced steel. The Yard manufactures steel in a basic electric furnace, under two slags: the first, a product of restricted oxidation of the melt; and the second, consisting of strongly basic and highly reducing materials, the product of several degasification and refining reactions. Table 2 gives the chemical composition of representative samples of each slag and of the metal they covered.

10. Degasification of the melt is accomplished in the furnace with ferrosilicon, ferromanganese, and ferrotitanium, and again in the ladle with calcium silicide. Melting down under a slag whose

Table 2

REPRESENTATIVE ANALYSES OF SLAG AND METAL

Composition of Oxidizing (Black) Slag, Per Cent

Period	SiO_2	CaO	MgO	MnO	FeO	Al_2O_3	P_2O_5	CaS	CaC_2	CaF_2	Ignition Loss
Beginning	29.62	17.26	19.83	13.30	13.80	5.24	0.06	0.09	0.10	...	None
Ending	29.67	19.44	22.22	12.15	9.82	4.81	0.04	0.11	0.06	...	None

Composition of Refining (White) Slag, Per Cent

Beginning	12.62	55.70	8.69	0.77	0.62	8.90	...	0.39	1.66	0.06	1.15
Ending	18.34	46.44	15.84	0.34	0.71	13.10*	...	0.57	0.22	4.86	0.00

Analyses of Three Heats, Oxidized to Various Degrees

Period	C.	Mn.	P.	S.	Si.	Ni.
	(Heat 404)					
	Composition, Per Cent					
After melting (1st prelim.)	0.20	...	...	...	...	...
After melting (2nd prelim.)	...	0.29	0.025	0.060	0.03	0.23
Middle of refining (3rd prelim.)	0.23	0.47	...	...	...	...
Final analysis	0.23	0.59	0.020	0.020	0.32	0.22
	(Heat 422)					
After melting (1st prelim.)	0.06	...	...	...	...	...
After melting (2nd prelim.)	...	0.12	0.011	0.050	0.01	0.31
Middle of refining (3rd prelim.)	0.14	0.36	...	...	...	...
Final analysis	0.24	0.58	0.020	0.020	0.29	0.25
	(Heat 411)					
After melting (1st prelim.)	0.01	...	...	...	...	...
After melting (2nd prelim.)	...	0.08	0.025	0.040	0.01	0.10
Middle of refining (3rd prelim.)	0.14	0.51	...	...	...	...
Final analysis	0.20	0.59	0.020	0.020	0.32	0.08

Approximate Amount of Flux Materials Used in Making Above Slags

Oxidizing Slag		*Refining Slag*[1]			
Plate scrap	12,500 lb.	Lime	250 lb.	50 per cent Fe-Si	50 lb.
Foundry scrap	8,500 lb.	Cement	94 lb.	85 per cent Fe-Mn	170 lb.
Iron ore	25-30 lb.	Fluorspar	90 lb.	70 per cent Fe-Ti	25 lb.
Limestone	250 lb.	Coke	15-20 lb.	Al. chips	20 lb.
Lime	250 lb.			Pig iron	300 lb.
CaO/SiO_2 Ratio	4.0 Approx.				

* This figure represents the sum of Al_2O_3 and TiO_2. From all indications, the TiO_2 appears to be less than 1.0 per cent.

[1] 0.15 per cent silicon is added before removing first slag. Immediately after slagging off, balance of ferrosilicon and ferromanganese is added. Final additions are: 0.05 per cent silicon, ferrotitanium, and calcium silicide.

oxidizing power is sufficient to bring the silicon in the charge to 0.02 per cent or less, together with the high degree of degasification achieved in the refining period, plus the fairly high percentage of new residual silicon (0.25-0.35 per cent) in the metal, results in the production of a metal remarkably low in occluded or dissolved gases. This practice, and the results obtaining from it, in the main are analogous to those discovered by C. McKnight, Jr.[3].

11. Regarding ductility, examination of tensile tests of annealed steel coupons show the metal to have an average elongation and reduction in area of 30.0 per cent and 50.0 per cent respectively. Physical properties of representative heats of the principal steels made are shown more completely in Table 3.

12. In the absence of any effort at regulation of residual oxygen in the metal, it is believed that these high values are the result of a very effective degasifying and desulphurizing practice. The calcium carbide, present in the second slag, desulphurizes

Table 3

ANALYSIS AND PHYSICAL PROPERTIES OF REPRESENTATIVE HEATS

Navy Department Specification Number	49Sli	46S33
Class	B	C-Mo.
Carbon, per cent	0.25	0.25
Manganese, per cent	0.59	0.67
Phosphorus, per cent	0.02	0.02
Sulphur, per cent	0.02	0.01
Silicon, per cent	0.36	0.28
Nickel, per cent	0.21	0.21
Molybdenum, per cent		0.40
Treatment	Annealed	Annealed
Tensile Strength, lb. per sq. in	70,250	73,500
Yield Point*, lb. per sq. in.	43,000	45,500
Elongation in 2-in., per cent	32.0	28.5
Reduction of Area, per cent	51.5	46.0
Bend	180°	180°

* Dividers.

the steel to so low a value (0.010-0.015 per cent) that there are not enough sulphide inclusions left to cause appreciable damage to ductility, even in the presence of a predisposition toward intergranular separation. The almost complete elimination of silicon during the melt-down, and its subsequent replacement with new silicon, also helps secure higher ductility.

Gamma-Ray Examination

13. The sixth and final factor, which indirectly assists in the production of sounder castings, as was previously stated, is gamma-ray examinations. Radiographs, when studied in relation to the effect produced by changes in design, molding, and melting technique, not only serve to locate and identify internal ailments, but also are instrumental in suggesting the proper remedy for overcoming them. Needless to add, many of the newer advances made in the art and science of founding have been made possible through radiography.

14. Anticipating possible criticism of the foregoing and of what follows, the authors hasten to add that the topics covered in paragraphs 4 to 13 do not treat principally of the causes of defects but of certain specific operations and conditions, proper and improper, and of their effect on the formation of certain defects. The authors realize that the causes for a great many casting defects are more often plural rather than singular in character, and that,

therefore, they can be caused by conditions other than the one discussed in each paragraph.

15. For instance, pinholes can be the result of several distinctly different major classes of unfavorable conditions, to wit: gasy metal, improper pouring technique, faulty mold construction, unsuited chemistry of sand and of metal; or they can be the product of a multiplicity of closely related unfavorable conditions within a single major class. For example, under faulty mold construction, the unfavorable conditions would be: high moisture sands, low permeability sands, hard ramming, insufficient venting, damp cores, rusty and wet internal and external chills, unsatisfactory chaplets, unsuitable facings, poor washes, non-refractory parting dusts, etc.

PART 2—THE PRINCIPLE OF DIRECTIONAL SOLIDIFICATION

16. The principle of controlled, directional, solidification has been expertly described in an article by the late George Batty[6]. A more extensive treatment of the laws governing its operation is contained in an article by C. W. Briggs, R. A. Gezelius and A. R. Donaldson[7]. For those few who are unfamiliar with its modus operandi, we venture the following elementary explanation. The physical laws governing the direction of solidification shall be considered first; and secondly, the genesis of internal unsoundness.

Effect of Heat-Flow on Crystallization

17. Solidification, or preferably crystallization, always progresses in the direction of the hottest metal, *i.e.*, along the lines of heat flow, the crystal growth taking place in the direction opposite to that of the flow. This process of growth in directions at right angles to the isothermal surfaces, and opposite to the lines of heat flow, governs the crystalline arrangement of all castings. The position and form of the heat isotherms, in turn, are determined by the geometry of the container and the conditions of cooling. The isographs in Figs. 1 to 3 illustrate the influence of the shape of the container on the heat isotherms and the consequent crystal arrangement in each.

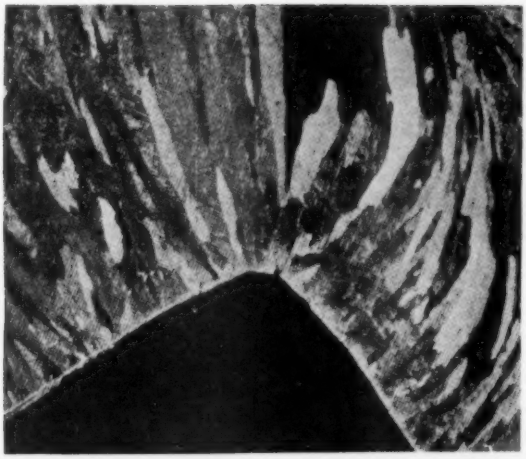
Solidification of Steel in a Mold

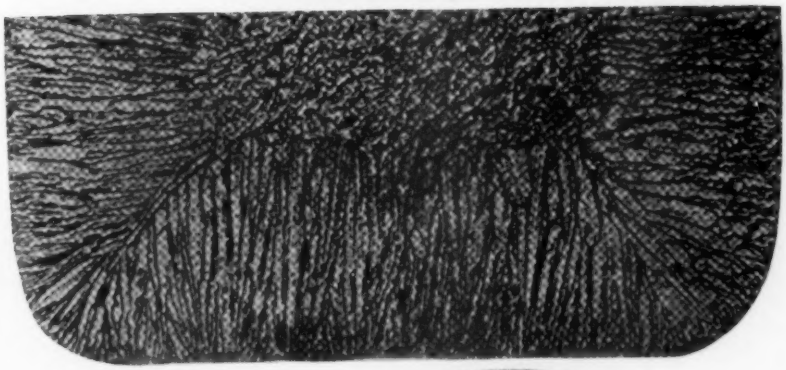
18. In the light of the foregoing, witness what happens after molten metal has been poured into a mold. Immediately upon contact of the molten metal with the relatively cold walls of either a

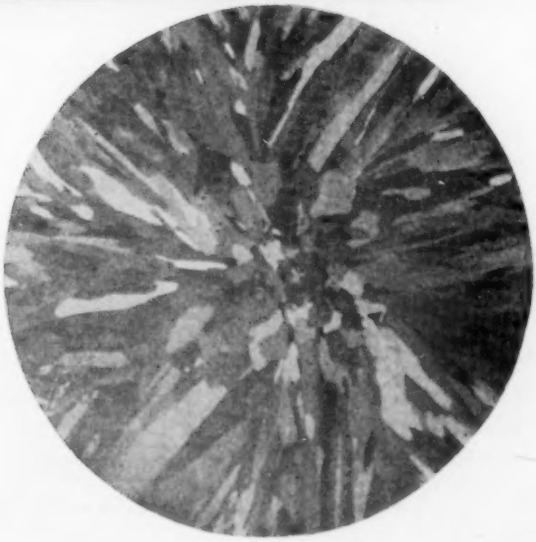
FIG. 1—ABOVE—DIAGRAM OF ISOTHERMS IN A CYLINDRICAL CASTING WHILE COOLING. BELOW—CRYSTALLIZATION OF HOT STEEL IN A CYLINDRICAL MOLD.

FIG. 2—ABOVE—DIAGRAM OF ISOTHERMS IN A QUADRANT OF A SQUARE CASTING WHILE COOLING. BELOW—CRYSTALLIZATION OF HOT STEEL IN A SQUARE CONTAINER.

FIG. 3—ABOVE—DIAGRAM OF ISOTHERMS AT A RE-ENTRANT ANGLE IN A COOLING CASTING. BELOW—CRYSTALLIZATION OF HOT STEEL AT A RE-ENTRANT ANGLE.







sand or a metallic mold matrix, an initial thin skin solidification occurs. This outside skin, consisting of exceedingly fine chill crystals, fixes the external dimensions of the ingot. Using the chill crystals for their base or nucleus, a somewhat different and larger type of dendritic crystallization then begins to form, or rather grow inwardly into the mother liquid. The arrangement and direction of growth of these columnar dendrites is determined by the isotherms peculiar to the mold being used.

19. Let us say that the mold in the present instance is rectangular in cross section. The isograph in Fig. 2 shows that the center is the hottest, and the corners, the coldest, parts of the ingot. From the graph in Fig. 4, it is evident that the greatest number of nuclei, and therefore crystals, will form at the corners. After an appreciable interval of time, a fewer number will form at the sides. The growth and orientation of these exceedingly long dendrites must needs be uni-directional, *i.e.*, normal to the isothermal surfaces. True, crystal growth, if unimpeded, is invariably uniform in four directions. In this particular instance, however, the walls of the mold prevent growth outwardly; the growing arms or secondary axes of adjacent crystals soon meet one another and arrest all growth in any of the directions parallel to the walls of the mold; and the only direction remaining for uninterrupted growth is per-

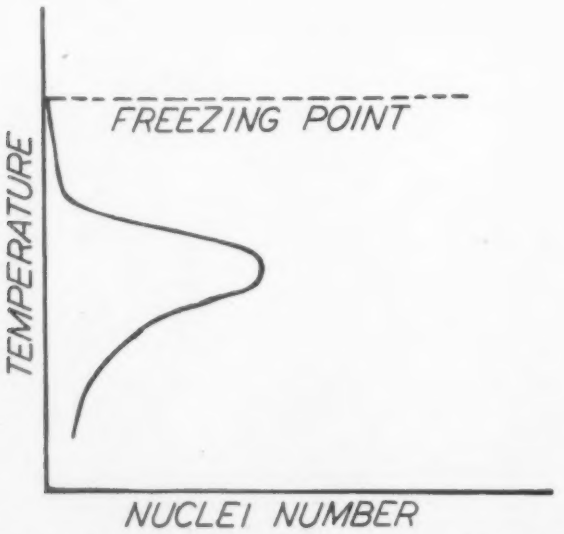


FIG. 4—TYPICAL NUCLEI NUMBER-TEMPERATURE CURVE. (ROSENHAIN).

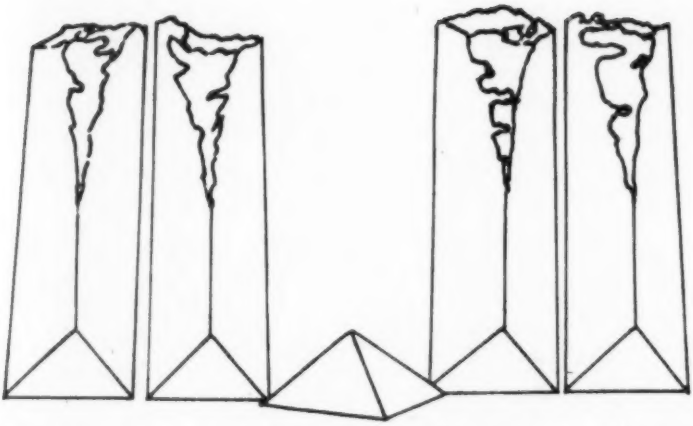


FIG. 5—BREAKDOWN OF A HOT-CAST METAL INGOT SHOWING THE EFFECTS OF DIRECTIONAL GROWTH (BREARLY).

pendicularly inward, where the metal is still too hot to allow of the formation of fresh nuclei.

20. Columnar crystals may, or may not, fill up the whole of the ingot, depending on the conditions prevailing during solidification and the amount and kind of deoxidizers used. Generally, in large ingots and in heavy sections, the center is cooled to the freezing point before the columnar crystals have grown across the ingot. If that be the case, the remaining metal then solidifies from many independent centers, the result being a center made up of fairly fine equi-axed crystals arranged in no particular geometric pattern.

21. As the dendrites advance inwardly from the four enclosing walls, with cooling, they eventually collide with each other on the geometric diagonals of the ingot. These diagonals, formed by the transcrystalline effect of the side walls, are clearly manifest in Fig. 2.

22. Solidification is a three dimensional phenomenon, *i.e.*, metal freezes across as well as up the cast member. As a result, the cold ingot assumes a structural arrangement consisting of four triangular prisms composed of long columnar crystals, one face of each prism corresponding to the interior face of the mold against which it formed. The growth of crystals from the bottom has proceeded in a similar manner, so that the four triangular prisms rest each on one face of a four-sided pyramid or base-cone as

shown in Fig. 5. This mode of crystallization leaves the steel potentially weak at several places, namely: the junction of each columnar crystal with its neighbors; the junction of each set of columnar crystals; and the junctions of the columnar and the equi-axed crystals. A large number of the cracks occurring in steels either originate or eventually locate themselves in the above zones of weakness.

23. Some metallurgists distinguish between two kinds of solidification, *i.e.*, progressive (laterally across the member) and directional (vertically up the member). In a great many instances, however, it is exceedingly difficult to disentangle the two. Pointing out the differences between them, it is stated that transverse or lateral freezing, aside from engendering certain zones of weakness in the form of cleavage planes, plays a relatively passive roll in the creation of defects. Because of this, foundrymen pay little, if any, attention to it. Upward or vertical freezing, on the other hand, exerts a decided influence on the efficiency of the feeding system, and therefore, on the solidity of castings. If properly directed, it is a potent force for the promotion of integral soundness; but if allowed to proceed randomly, without any attempt at regulation of temperature gradients, it will cause a disastrous proportion of the castings to be unsound. The fundamental difference between the two kinds of freezing is that the direction of the latter can be controlled, while that of the former cannot.

Causes of Solidification Defects

24. Concerning defects, in addition to the internal cracks referred to in the preceding paragraph, there are other serious solidification ailments from which castings frequently suffer, namely: pipe (major, secondary, and micro), internal shrinkage draws, and center-line weakness. The cause for their formation is the diminution in volume (approximately 3 to 5 per cent) which normally occurs during the transition of the metal from the liquid to the solid state. As the outer layers of liquid metal become progressively densified by solidification, other liquid metal from the hotter interior portions flows outwards to the solid crystals which have already separated. So long as this influx of liquid metal to the solidifying areas can take place, the production of a solid casting is possible; when the supply fails, internal cavities result. Piping can be eliminated from the casting by localizing it in properly propor-

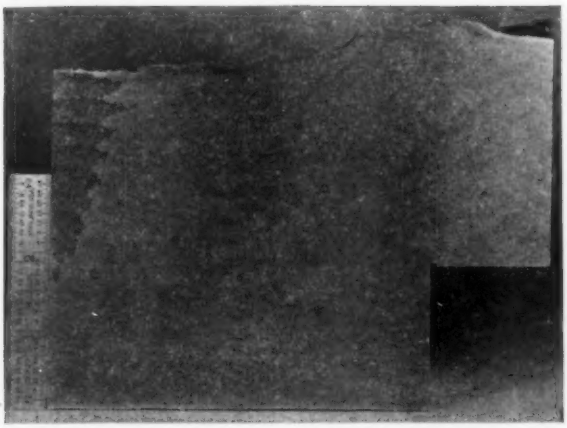


FIG. 6—SECTION OF A STEEL CASTING SHOWING CENTER-LINE SHRINKAGE DEFECTS. NOTE THAT THEY ARE LOCATED IN THE NON-ORIENTED CENTRAL ZONE OF CRYSTALS.

tioned, suitably-located, and efficiently-feeding shrink-heads or risers.

25. The stubbornest of all defects is center-line weakness. It is a defective condition of metal consisting of tiny (micro and macro) crevices with dimensions often on the order of a fraction of a millimeter, with irregular and ragged outlines (Fig. 6), and with non-oxidized walls. With reference to the equilibrium diagram of iron-carbon alloys, center-line weakness is believed to occur in the temperature range bounded by the liquids and solidus lines, and is formed by the contraction on freezing of the last portion of the liquid enclosed by surrounding partitions. Thus, no center-line weakness is to be found in the oriented peripheral zone of castings and ingots in which basaltic crystallization progresses uniformly inward without encircling any remaining liquid. The defect is found, however, in the non-oriented central zone of crystals, where dendrites growing in various directions meet.

Effect of Mold Reversal

26. It has been repeatedly demonstrated by good authority that freedom from the above defects can be obtained with controlled, directional, solidification. In Figs. 7 and 8, is indicated the manner in which a sound and an unsound condition of metal is obtained, using controlled, directional, solidification and an orthodox foundry method of casting respectively. The contour lines mark

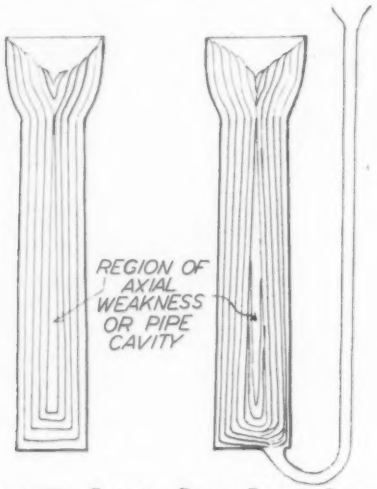


FIG. 7—LEFT—TOP-POURED CASTING. RIGHT—BOTTOM GATED CASTING (BATTY).

the crystallization of successive skin thicknesses and show the progress of metal immobilization. In Fig. 7—Left, the example is top-poured, there being no sand ingate to the mold. In Fig. 7—Right, the example is bottom-gated, as is customary with most steel castings, while in Fig. 8, the example is bottom-gated into the riser and, after pouring is completed, the mold is reversed through an angle of 180° to bring the riser into its proper feeding position in relation to the casting.

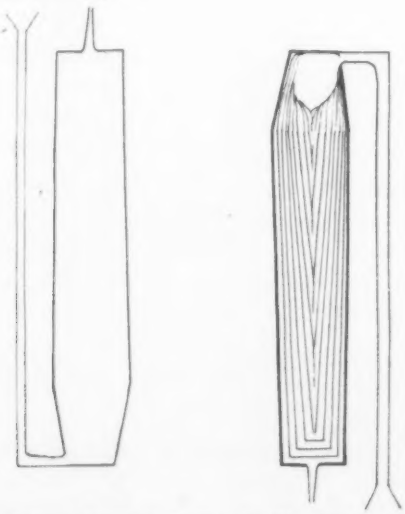


FIG. 8—CASTING SHOWING RESULT OF 180° REVERSAL (BATTY).

27. It will be seen that, while example, Fig. 7—Left, presents evidence of little or no adverse temperature gradient, example Fig. 7—Right, shows considerable evidence of such an adverse temperature gradient. Fig. 8 illustrates how a favorable temperature gradient is produced with complete reversal of the mold. From a study of the sketches, it is evident that soundness is assured only when the direction of solidification is progressively upward from the bottom to the feed-head of the mold. To insure freezing of the metal in the upward direction, there must be imposed upon the cooling system, a decided temperature difference between the top and bottom metal, *i.e.*, the temperature of the metal in the feed-head must be higher than that of the metal in the bottom of the mold.

28. Practical difficulties often deter the establishment of a favorable temperature gradient in a great many castings, especially when orthodox foundry methods are followed in making them. The difficulties can be circumvented, however, by an ingenious use of one or more of the following methods of casting manufacture.

1. Banking or Partial Reversal, 20-45°.
2. Top-pouring of Risers.
3. Heading.
4. Gating—parting, multiple, and stepwise.
5. Chilling, Coring, Design.
6. Padding—outside, inside, eccentric.
7. Sectioning or Partitioning of Castings.
8. Preheating the Cope.

PART 3—SPECIFIC CASES

Anchor Shanks—Illustrating Control by Banking

29. Of the many marine castings that the foundry makes, anchor shanks are probably the most adaptable to controlled solidification. They are long, slightly tapered, solid members of rectangular cross section with liberally radiused corners. Their design is completely free from re-entrant angles, differential sections, and changes in direction. The absence of all but one small internal core in the shackle-bolt hole also makes for integrity in the subject castings. Fig. 9 depicts the general outline of a shank for a 20,000 lb. stockless anchor, with gate and feed-head attached.

FIG. 9—SHANK FOR 20,000 POUND STOCKLESS ANCHOR WITH GATE AND FEED-HEADS ATTACHED.

30. The procedure of mold manipulation involved in directing solidification up the shank is quite simple. The mold is tilted at a small angle (20°) on a bar or rail on the foundry floor so that the ingate and feed-heads are located at the low end of the mold. After pouring is completed and the vent sealed, the mold is reversed through an angle of about 20° to bring the feed-head into the requisite superior position in relation to the casting.

31. Using the above practice, it is possible to produce overall temperature gradients of approximately 700-900°F. in the shank. Inasmuch as the efficiency of the feeding or heading system is a function of the temperature gradient imposed on the solidifying metal, it is apparent that whatever can be done to widen the temperature gap between the vertical extremities of the casting will result in a sounder product. In this connection, the following additional steps are taken to secure a steeper heat gradient: (1) slow pouring; (2) filling feed-heads from the top; and (3) heat-insulating the top of feed-heads.

32. *Slow Pouring.* It is not difficult to see how slow pouring creates increased temperature differences. Metal solidifies as a result of transference of heat from itself to the mold. In its transit through the mold, it cools by an amount which is proportional to the duration of its contact with the mold, and the ratio of the contacted mold area to the thickness of the metal stream passing over it. The essential feature of pouring, therefore, is that the molds shall be filled as slowly as practicable.

33. Too rapid filling of the mold results in greatly reduced temperature gradients, and oppositely, too slow pouring is produc-

tive of castings having a defective surface, scabbed and pock-marked on the cope side.

34. Scabbing, by slow pouring, occurs in the following manner. The drag, or bottom surface of a mold generally escapes injury because the weight of the overlying hot metal overwhelms all lifting and bulging forces generated within it. No such damping action is exerted on the disruptive forces acting on the cope or top surface. Here the intense radiant heat, given off by the slowly rising metal beneath, acts on the cope, causing it to crack and swell. The cracked and loosened surface is then either pulled down by gravity or dislodged by the wiping action of flowing metal.

35. This burning down of the cope can be remedied in one of four ways: (1) faster pouring, (2) more thorough nailing of the cope surface, (3) an increased use of crabs in the cope, or (4) strengthening the bond of the sand in the cope with more bentonite. The subject shank was poured with approximately 1.0-in. rise of metal in the mold per second. This speed was obtained with a 2½-in. pouring nozzle and a 4-in. in-gate.

36. *Casting Temperature.* A word is probably in order concerning the effect of casting temperature on the quality of the metal. Pouring temperatures which are too low, even if sufficiently high to avoid cold shuts, may not permit risers to perform their primary function of feeding the casting or to carry off slag, dirt and dross. Casting temperatures on the other hand which are too high, aside from increasing liquid shrinkage and quite apart from other disadvantages attaching to them, reduce the rate of solidification, because the excess heat of the metal is communicated to the mold before the freezing point of the metal is reached, so that the thermal capacity of the mold is largely exhausted before solidification begins. The resulting very gradual solidification produces not only a very coarse structure, but allows the occurrence of serious segregation. It is, therefore, an almost universal rule that casting temperatures should be kept as low as possible, consistent with adequate fluidity of the metal to allow proper filling of the mold. The approximate casting temperature of the metal used in making the shanks was 2850°F.

37. It was stated earlier that the practice of filling up feedheads from the top, after the pouring of the casting proper is completed, is further assurance that the metal in the upper levels of

the mold will be hottest. Covering the risers with anti-piping material retards their cooling considerably and thus it, too, tends to promote better feeding. The riser on all shanks was treated in just such a manner.

38. The data, given in Table 4, relates to a shank for a 20,000 lb. anchor. It will be noted that dry steel facing sand and used sandblast sand were used in making the mold and core respectively. The reason for this is that the relatively harmonious design possessed by the shank presents no problem in mold resistance. Sandblast sand cores impart a very smooth finish to the casting surface; they are not used where a high order of ready and immediate collapsibility is desired.

Anchor Crowns—Illustrating Control by Top-Pouring of Risers

39. Instances where top-pouring is employed, *per se*, as a means to secure directional solidification are rare; instances where it is used conjunctively with other methods are legion. Top-pouring is accomplished in one of two ways: (1) either the casting together with its risers, or (2) the risers alone, are top-poured. When it is not feasible to pour a casting via a top gate for fear of excessive erosion of the mold, the next best procedure is to bottom-pour the casting up to the level of the risers, and then top-pour the risers. The latter practice is the more common.

40. Concrete examples, illustrating the employment of the latter method for directing solidification, are anchor crowns and large monel metal propellers. Both of these castings, by design, are subject to differential freezing. The thin flukes on the anchor and the thin blades on the propeller congeal rapidly, while the more massive sections, particularly the feed-heads, remain fluid for a long time. Even if the above were to be bottom-poured completely, it is apparent that the adverse temperature gradient produced by bottom-pouring would not only be short-lived but would soon reverse itself into a favorable one by the lower surface-area to volume ratio of the heavier base and feed-head sections.

41. The remarks made under anchor shanks, concerning the speed of pouring, temperature of metal, and mold resistance, also are applicable to the crown. The data shown in Table 4, pertains to the making of 20,000 lb. anchor crowns.

42. Two undesirable conditions attended the manufacture

Table 4

MOLD MATERIALS, STEEL DATA, FOUNDRY PRACTICE AND HEAT TREATMENT FOR MAKING ANCHOR SHANKS AND ANCHOR CROWNS

	Anchor Shank	*Anchor Crown*
Mold Materials		
Facing Sand (See Table 1—Part 1)	No. 2i	Cope: Nos. 3d, 3e Drag: Nos. 2i, 2j
Backing Sand (See Table 1—Part 1)	No. 4b	No. 4b
Core (See Table 1—Part 2)	No. 5e	..
Internal Cores (See Table 1—Part 2)	..	No. 5e
External Cores (See Table 1—Part 1)	..	Nos. 2i, 2j
Steel Data		
Steel Grade	Bw	Bw
Pouring Temperature, °F	2875	2850
Nozzle Size, in	2½	3½
Pouring Time (Not including riser) sec	25	55
Rate of Metal Rise in Mold, in. per sec	1.0	..
Founding		
Banking Angle of Mold, Degrees	20	..
Temperature Gradient Obtained, °F.*	950	..
Size of Feed-head	17-in. rd. x 26-in.	..
Size of Ingate, in	4	4 (Terra cotta)
Size of Risers	..	2—11-in. rd. x 14-in. 1—24-in. rd. x 30-in.
Weight of Shank, Riser and Gate, lb	5,900	..
Weight of Shank, lb	4,820	..
Weight of Crown, Risers and Gate, lb	..	19,300
Weight of Crown, lb	..	15,500
Heat Treatment		
Upheat, hr	18	18
Hold, hr	30	30
Temperature, °F	1650	1650
Cooling, hr. in Furnace	24	24

* Measured with thermocouples immersed in metal to a depth of 1-in. in the bottom-most and top-most locations of shank.

of large (20,000 and 25,000 lb.) anchor crowns, *viz.*, scabbing of the cope surface, and low dynamic strength at 42-52°F. in the heavier sections.

43. Navy Department Specification 6A2 for stockless anchors requires that they be drop-tested from a 12-ft. height. Fig. 10 pictures a macro-etched section of an anchor fluke which had failed in cold weather in the drop test. The physical strength of the metal in close proximity to the fracture, and in the locations indicated on the photograph, is recorded in Table 5. Susceptibility to cold brittleness under impact was partially overcome by increasing the holding time, on annealing, from 30 to 38 hr., together with the employment of approximately 1000 lb. of internal chill bars (½-in. thick by 1½-in. wide by 12 to 36-in. long) arranged checkerwise in the flukes. It is the policy of the foundry to rarely resort to the use of internal chills, in fact, not at all, in small size sections (up to 9-in. thick). Regarding their use in heavy sections, there are occasions, such as this one, when their use is well nigh unavoidable.

44. Scabbing was eliminated to a large degree with faster pouring, with increased nailing of the cope, and by shading the cope with internal chills against the intense heat of rising metal.

Globe-Valve Bodies—Illustrating Control by Heading

45. Control by heading is practiced on small castings whose design is either not amenable to, or makes uneconomical the use of, the reversal methods of casting. Favorable temperature gradients are produced by risers only when their ratio of surface-area to

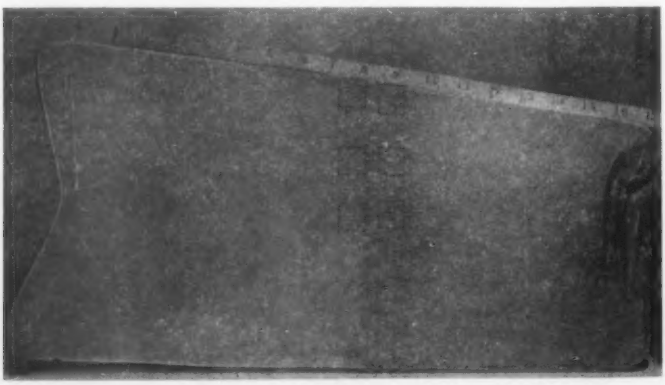


FIG. 10—CROSS SECTION OF 20,000 POUND ANCHOR CROWN. OBSERVE THE SOLIDITY OF METAL. SQUARES MARK LOCATION OF TEST SPECIMENS TAKEN FOR TABLE 5.

Table 5

PHYSICAL PROPERTIES ON A 20,000 LB. ANCHOR CROWN
(After Standard Annealing Treatment)

Location of Specimen	*Tensile Strength, lb. per sq. in.*	*Yield Point[2], lb. per sq. in.*	*Elongation in 2-in., per cent*	*Reduction of Area, per cent*	*Izod Impact[3], ft.-lb.*		
Coupon[1]	67,500	41,250	34.0	54.5	...	...	...
Outside[4]	65,500	37,250	28.0	39.1	36.0	37.5	41.5
Midway	66,250	40,000	20.0	25.8	34.0	33.0	34.0
Center	63,250	40,000	17.0	24.1	39.5	25.0	35.5
TREPANNED SPECIMENS RE-ANNEALED AT 1650°F. FOR 2 HR.							
Outside	68,500	45,000	35.0	54.4	42.5	47.5	41.0
Center	68,750	45,750	20.0	26.8	45.0	41.0	50.5

TRANSMISSIBILITY OF IMPACT LOADS AT 80° AND 32°F.[5]

Location	*Single Width (10 mm.)*	*Double Width (20 mm.)*	*Temp. of Test*	*Heat Treatment*
Outside	23.0	42.5	80°F.	Standard Anneal
Outside	26.0	50.0	80°F.	Trepanned and Re-Annealed at 1650°F. for 2 hr.
Midway	13.5	15.0	32°F.[6]	Standard Anneal
Midway	18.5	42.5	32°F.	Trepanned and Re-Annealed at 1650°F. for 2 hr.

[1] Coupon attached to underside of fluke.
[2] Divider method.
[3] 10 mm. square, V-notch, 120 ft-lb. setting.
[4] Specimens taken from failed anchor crown. See Fig. 10.
[5] Charpy type impact specimens, one 10 mm. square and the other 10 mm. thick by 20 mm. wide. Hammer let fall from 220 ft.-lb. setting.
[6] Specimens were held for one hour on melting ice, then tested.
NOTE: Dimensions of section tested = 9-in. thick by 12-in. wide by 30-in. long.

volume is considerably less than the ratio of surface-area to volume of the casting which they surmount. This is predicated upon the fact that the velocity of solidification is a constant, that is, that at any definite time after pouring, the weight or volume of steel solidified per square inch of mold surface is the same[4]. The curves in Figs. 11 and 12 show the relation between the volume of steel solidified per unit surface-area and the time which has elapsed after pouring.

46. It is apparent from a study of the graphs, that the ideal form of riser is, most probably, a sphere but there are practical difficulties in economically applying such a form of feeder. For the same volume, the next most efficient form of riser or reservoir of temperature is the cylinder. Following this come the square, and then the flat rectangular types of risers. To illustrate by way of a concrete example, Table 6 shows the relative feeding efficiencies of differently shaped risers of identical volumes.

47. Steel castings often give the impression of being too heavily burdened with risers. The liquid shrinkage of steel is only 3 to 5 per cent and yet the volume of metal required in the feed-

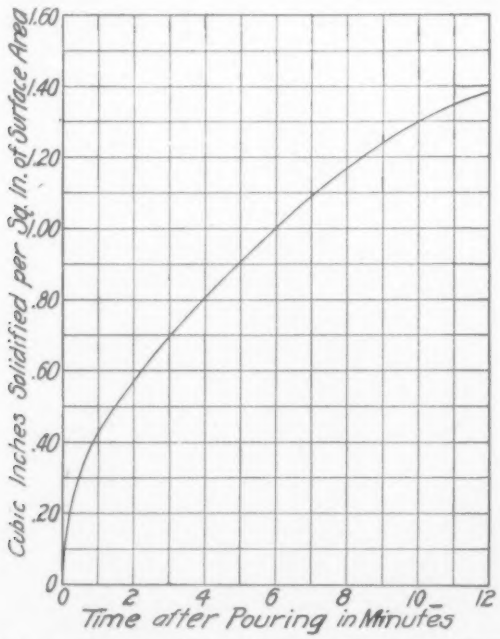


FIG. 11—RATE OF SOLIDIFICATION OF STEEL IN DRY-SAND MOLDS WITH RELATION TO SURFACE AREA (BRIGGS AND GEZELIUS).

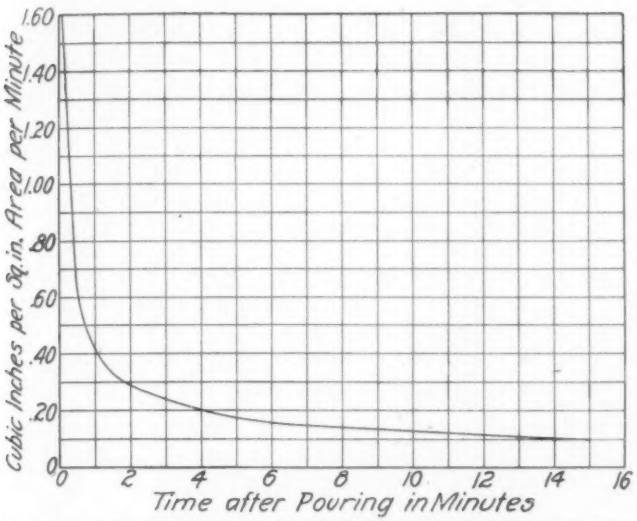


FIG. 12—RATE OF SOLIDIFICATION IN DRY-SAND MOLDS BASED ON VOLUME SOLIDIFIED (BRIGGS AND GEZELIUS).

Table 6

FEEDING EFFICIENCIES OF DIFFERENTLY SHAPED RISERS OF IDENTICAL VOLUMES

Form and Size of Riser	*Vol., cu. in.*	*Weight, lb.*	*Area, sq. in.*	*Amount Solidified in 1 min., lb.*	*cu. in.*	*Time to Completely Solidify, Min.*
Sphere: 6-in. diameter....	113	32.0	100	12.1	42.7	7.2
Cylindrical:						
4¼ rd. x 8.0-in.....	113	32.0	120	14.5	51.2	4.7
Square: 3⅝x3⅝x8⅝-in....	113	32.0	135	16.3	57.5	3.6
Plate: 2¼x6¼x8-in.....	113	32.0	160	19.4	68.4	2.7
Plate: 1$\frac{11}{16}$x10$\frac{5}{16}$x8-in.....	113	32.0	220	26.6	93.8	1.5

heads is 25-50 per cent of the casting. There are times when the use of large risers is warranted, namely: when their form is such that they have a low thermal efficiency; when they are intended to be used as reservoirs of temperature to direct solidification; and when the cope selected for the job is too high. Flanged castings, like the one shown in Fig. 13, owe their solidity to the effective feeding of their large risers. The area to volume relation between the casting of Fig. 13 and one of its risers is the following:

	Area, sq. in.	*Volume, cu. in.*	*Weight, lb.*	*Ratio, V/A*	*Metal Immobilized* 2 min. After Pouring*	*3 min.*
Casting	1240	875	248	0.70	203 lb.	Solid
Riser	224	240	68	1.07	37 lb.	46 lb.

* Calculated from Fig. 11.

48. The mold for the above casting was made in green steel facing sand (mixture 1d, Table 1) so as to permit the flanged ends to pull toward each other with the least possible resistance. Hindrance to contraction was lowered still further by using a baked oil sand core (mixture 7d, Table 1) topped off with green steel facing sand (mixture 2a, Table 1). If the shell of the baked bottom core be not too thick, composite cores of this kind help avoid longitudinal cracking of the casting. Vee-notching the shell on the inside has been suggested as still another possible means for increasing core collapsibility. Attention is directed to the smoothness of surface possessed by these castings.

Struts—Illustrating Control by Gating

49. Gates, the actual points at which molten metal enters the mold, not infrequently provide an excellent means for directing solidification. Of the three fundamental classes of gates, top, parting, and bottom, only the first two are capable of producing favorable temperature gradients. This they do by virtue of their elevated location. All other things remaining equal, it is obvious that the portions of the casting farthest away from the gate or entering point of the metal will freeze first and that freezing will tend to be directed from this farthermost position towards the gate. Thus a gate situated at or near the top of the casting will direct solidifica-

FIG. 13—SEVEN INCH VALVE BODY, ILLUSTRATING CONTROL OF SOLIDIFICATION BY HEADING. OBSERVE THE SMOOTHNESS OF THE STEEL SURFACE.

tion up to itself; while a gate situated at the bottom of the casting will, by the same token, direct solidification down to itself. The direction of the latter, as explained elsewhere, is counter to that required for efficient feeding.

50. Large castings are rarely, if ever, top-gated. No sand mold can withstand for long either the cutting action or the impact of a vertically falling column of steel. The attendant bottom splash and turbulence of metal also inflict severe damage upon the casting. Because of this, parting and bottom gates are used almost exclusively. Parting-gates are considerably less damaging in their effect upon the mold. In fact, the tendency to mold erosion is almost entirely eliminated when several of these gates supply the metal to the mold simultaneously. Multiple gating slows down the speed of the metal, causing it to run down the banks of the mold in quiet, and smoothly descending streams. Parting-gates of the multiple type are shown in Figs. 13, 18, and 21.

51. Bottom-gating, despite the adverse temperature gradients it creates, enjoys the greater popularity among foundrymen. It is regarded as being the orthodox method for gating castings. The reason for its widespread popularity is its ability to introduce metal into the mold with a minimum of metal and mold disturbance.

52. On occasion, bottom-gating can be made to function in a manner analogous to top-gating. By way of an actual illustration, reference is made to Fig. 14—Top which shows a large strut casting with a single downrunner or sprue connected to the hub section through three gates. All three of them lie in the same vertical plane but at different elevations: one at the bottom, one in the middle, and one close to the top. During the pouring of the mold, nearly all the metal in the lower levels is introduced by way of the bottom gate; that in the higher and topmost levels, by way of the middle and top gates respectively. And lastly, after the casting proper has been poured, each of the three risers is individually top-poured.

53. Immobilization of metal in the direction of the feed-heads is further assured by the internal padding of the bore Fig. 15 (obtained by putting on 0.44-in. per ft. taper on the core), and the placement of two external metal mounds directly over the junction between each arm and hub. By gating and padding in this man-

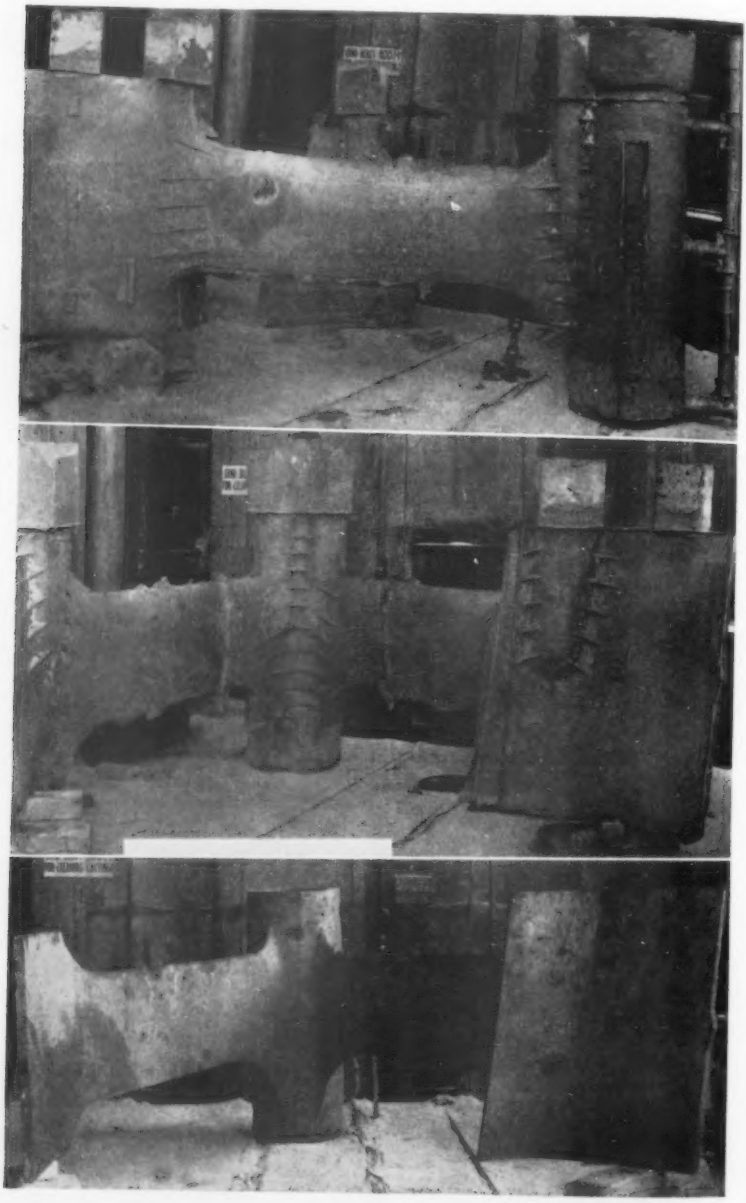


FIG. 14—TOP—TWO-ARM STRUT, AS-CAST, SHOWING GATING, RISER, AND OUTSIDE PADDING. CENTER—SAME, AS-CAST, SHOWING DETAIL BETWEEN THE ARMS. BOTTOM—SAME, FINISH-MACHINED.

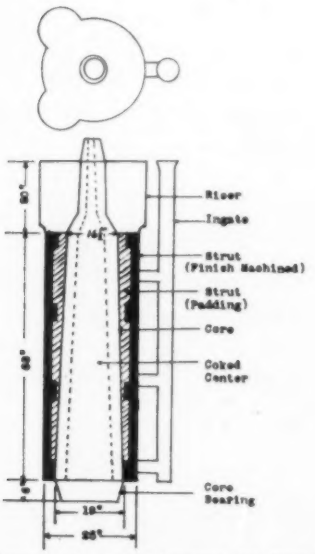


FIG. 15—SHOWING INTERNAL PADDING ON BORE OF STRUT.

ner, and top pouring of risers, there is thus produced a pronouncedly favorable temperature gradient in both mold and metal which predicates throughout the whole casting.

54. Five to eight min. after pouring, the drawbacks in the mold are loosened to permit the casting to move in with the least possible mold resistance. Twenty min. after pouring, all mechanical restraint on the drawbacks is removed.

55. Until the above practice had been developed, considerable difficulty was experienced in obtaining good castings. The substitution of external pads for external chills between the arms and hub, and the employment of a readily detachable green sand drawback in the crotch, aided greatly in the production of sound struts.

56. The mold for the above casting consists essentially of a large drag and three small copes for the risers. In the drag, and between the arms of the strut, there are three drawbacks: one against each of the two arms, and one in the crotch of the arms. Both dry and green sand mixes have been used successfully in the two-arm drawbacks, the green sand generally yielding the superior product with respect to surface appearance and freedom from hot tears between the arms and the hub. The core is made from dry steel sand (mixture 2i, Table 1) and extends beyond the top of

the riser. Preceding the positioning of drawbacks and cores, the mold is dried with salamandrine heat. Four-in. terra cotta sleeves are used for the gates and sprue. Additional data in Table 7 give information on the amount of metal in risers and padding.

Table 7

METAL DISTRIBUTION IN MAIN (TWO-ARM) STRUT CASTING

	Weight, lb.	*Per Cent of Total Weight Used*
Casting with Gates and Risers Attached..	14,200	100
Finished Product, Machined.....	7,140	50
Gates and Risers, Ribs and Fins.....	2,800	19
Outside Padding, Mounds.....	700	5
Metal Removed from Bore.....	3,560	26

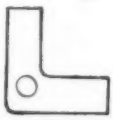
Low Pressure Turbine Casings—Illustrating Control by Chilling

57. Present day foundry technology looks askance upon the use of internal chills, and seldom relies upon external chills alone for controlling the direction of solidification. The primary purpose of externally applied chills, as used today, is to eliminate adverse local temperature gradients set up at junctions of thin and thick sections, and at locations of extra mass (hot spots) found at positions of joining sections. Hot spots, and junctions of dissimilar sections, are the loci of stress generation, stress concentration, and hot tear formation. This is so for the reason that thick sections require more time for solidification and cooling than thin sections. It is not impossible for a thin section, integrally connected to a heavier one, to be completely solid and appreciably cooled while the heavier section is still solidifying. The temperature gradients so established will result in different rates of contraction and hence the formulation of stress. Centralization of stresses occurs at sharp corners and abrupt changes in section. Cracking will occur at the weakest section, which, of course, will be the hottest section.

58. Hot spots may be searched out by the inscribed circle method of Heuvers[5] as illustrated in Fig. 16 (a). They can be eliminated with design, external chilling, and internal coring. The first and last operate by equalizing the sections; chills, by equalizing the rates of cooling of different sections. The joints shown

Square corners.
Area of defect
= 2.05 sq. in.

I.C. = ½-in. R.
O.C. = 4½-in. R.
No defect.

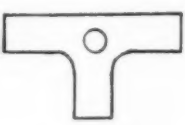


I.C. = ½-in. R.
O.C. = 1-in. R.
Core: 2-in. diam.

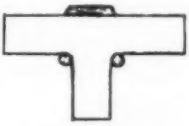
I.C. = ½-in. R.
C.A. = 0.70 sq. in.
E.P. = 1.87-in.

Square corners.
Area of defect
= 3.5 sq. in.

I.C. = ½-in. R.
O.R. = 5-in.
No defect.



I.C. = 1½-in. R.
Cored 2-in. dia.
hole.
No defect.



1-in. dia. chills plus
1-in. plate chill
C.A. = 5.31
E.P. = 5.56-in.

45° angle.
Area of defect
= 3.3 sq. in.

I.C. = ½-in. R.
O.R. = 4½-in.
No defect.

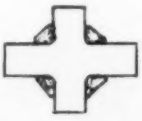
I.C. = ½-in. R.
Core: 2½ x 2-in.
ellipsoid.

1-in. dia. chill plus
1-in. chill plates
C.A. = 8.78
E.P. = 9.05-in.

Square corners.
Area of defect
= 5.5 sq. in.

I.C. = ½-in. R.
O.R. = 5-in.

I.C. = ½-in. R.
Rectangular core.
Area core: 5.56
sq. in.



Triangular chills
C.A. = 10.76 sq. in.
E.P. = 15.2-in.

60° angle.
Area of defect
= 2.7 sq. in.

I.C. = ½-in. R.
O.R. = 5-in. R.

I.C. = ½-in. R.
Triangular core.

Triang. chill plus
1-in. chill plates
C.A. = 8.70
E.P. = 10.14-in.

I.C. = INSIDE CORNER
O.C. = OUTSIDE CORNER
C.A. = CHILL AREA
E.P. = EFFECTIVE PERIMETER
O.R. = OUTSIDE RADIUS
R. = RADIUS

FIG. 16—FIVE FUNDAMENTAL METHODS OF JOINING SECTIONS AND HOW JOINTS CAN BE MADE SOLID.

in Fig. 16 illustrate the five basic ways in which sections join, and the manner of mass distribution necessary for the avoidance of hot spot formation. Excepting for the arrangement and a few minor modifications, the original sketches are those of Briggs, Gezelius and Donaldson. It is evident that not all liberal radii are beneficial. Those imposed upon the joint by the addition of metal aggravate the temperature gradient in the hot spot; those formed by the subtraction of metal, ameliorate it. It must be remembered, too, that though some designs are excellent from the standpoint of obtaining solidity of section, they may be very poor designs from the standpoint of uniform transmissibility of stress.

59. Actual instances, illustrating the application of chilling to areas harboring local adverse temperature gradients, are shown in Figs. 17 and 18. In Fig. 17, numerous *V*, *X*, and *Y* joints are evident, some very remote from the feed-heads. Using the method of inscribed circles for determining the size of hot spots, the diameter of the inscribed circle at the intersection of the *X* is 1¾-in. as compared with that of ¾-in. in the intersecting arm. The hot spot in each of the *X* joints was eliminated by means of four large triangular chills: two 3x3x5-in., and two 2x2x3-in. in cross sec-

FIG. 17—I. P. TURBINE CASING, SHOWING *V*, *Y*, AND *X* JOINTS.

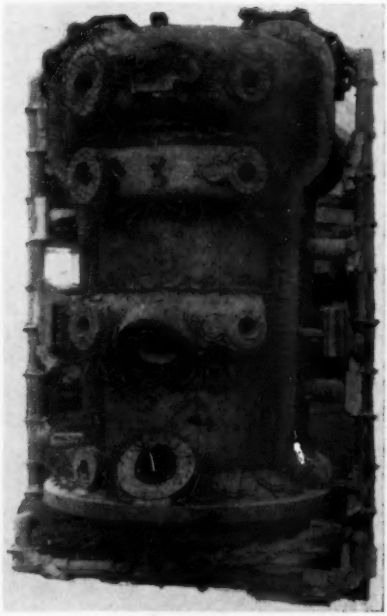


FIG. 18—H.P. TURBINE CASING (TOP HALF). ILLUSTRATING APPLICATION OF CHILLING FOR CONTROLLING SOLIDIFICATION.

tion. The total effective perimeter and the cross sectional area of the four chills were 20 in. and 12.5 sq. in. respectively. No chills were used on the *V* or *Y* joints. Instead, the entire joint in every case was tapered (¼-in. per in.) and the leg of the *Y*, spread as pictured. In this manner, the potential area of shrinkage was chased into the padding on the inside of the casing, whence it was removed with the padding, during rough machining. Radiographic inspection of the joints found them to be sound.

60. Fig. 18 is an example of a more extended use of chilling for the control of solidification. It will be noted that nearly every re-entrant angle contains a chill. The manner of abstracting heat from heat-retaining pockets is clearly manifest. Chills are present in all places where adverse temperature gradients tend to build up, *viz.*, at the foot of isolated pads, bosses, flange necks, and at the intersection of all planar surfaces. One-inch, round, steel chills were used on the subject casting. Comparing chilling methods with padding methods, it is stated that a greater degree of soundness is obtained in castings of the subject type with the latter.

Struts and Turbine Casings—Illustrating Control by Padding

61. *Struts.* Molds of big-end-up design were proposed and used experimentally by steel producing plants more than 50 years ago. Since that time, they have been more and more widely used in industry until today their use is well nigh universal. Despite their widespread use and their proved worth in the manufacture of ingot steel, tapered molds were not used by foundrymen for many years. It is only recently that steel foundries began applying taper to steel castings. Foundrymen are now convinced that, in order to avoid loose texture and axial shrinkage cavities in the body of a massive casting, the chamber of the mold must be of big-end-up design and enough larger in top cross-section than in bottom cross-section so as to cause the metal to solidify progressively upward.

62. There are still many foundries which are loath to adopt the tapered or padded design because, in their opinion, it adds unduly to the cost of production. The Yard's experience negates this argument. The cost of patterns for padding, the cost of the steel in the padding and the labor involved in its removal, plus the increased cost of heat treatment due to longer soakouts at the annealing temperature, add up to a very small sum indeed when compared with that normally expended upon their repair (preliminary exploring, buttoming out, welding, re-x-raying, stress relieving, pressure testing) of defects inherent to the unpadded design, or the replacement of the entire casting with a second, or possibly a third, new one. The consequent loss of time and delay in production is also costly.

63. The only disadvantage attached to the padded design, is the diminution in strength and ductility suffered by the casting. This is the penalty exacted by increased mass. Inasmuch as the application of padding herein was restricted to one side only (the other side always retaining the cast skin), the deleterious effect due to mass was slight. The outside metal on heavy castings is generally of excellent quality to a depth of 1-in., possessing physical properties often comparable to those of individually cast coupons (See Fig. 10 and Table 5).

64. The fact should not be overlooked that the steel castings industry is producing castings of highly complicated design that have remarkably uniform properties throughout sections of unequal mass. Such uniformity in properties is achieved by skillful

gating and molding practices, by good melting technique, and by subsequently heat-treating the castings in a way to minimize as much as possible, the influence of change in section.

65. It is added that all welding of minor defects and structural attachments is done after annealing. Annealing also precedes all chipping and rough machining operations. Castings have been irreparably damaged by having been welded and by having been chipped in the green state.

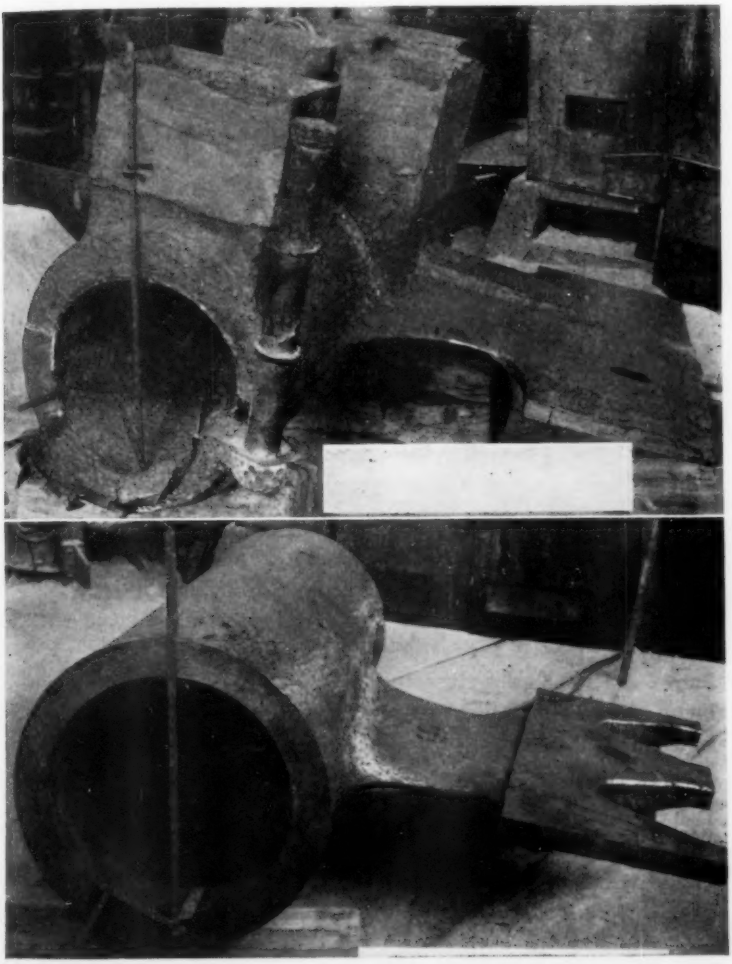


FIG. 19—TOP—INTERMEDIATE STRUT, AS-CAST, SHOWING PADDING AS APPLIED TO HORIZONTAL CYLINDERS. BOTTOM—SAME, FINISH-MACHINED.

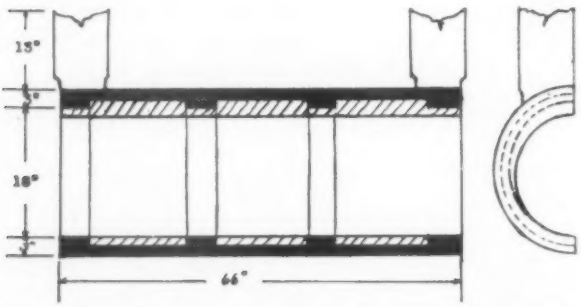


FIG. 20—SHOWING PADDING IN BORE OF HORIZONTALLY-CAST STRUT.

66. The strut in Fig. 19 is an example of padding as applied to a horizontally made cylinder. The barrel is 66 in. long with outside and inside diameters of 25 in. and 18 in. respectively. To obtain directional solidification, the walls are eccentrically tapered from a minimum thickness of 3 in. in the drag to a maximum of 4 in. in the cope (Fig. 20). Further steepening of the temperature gradient is secured by top-pouring of risers and by their massiveness as well. Collapsibility in the core is obtained by topping it off with green sand.

67. An alternative method, which is being contemplated for making intermediate struts, is that employed on the main two arm struts. Vertical molding is productive of a greatly reduced cope area and therefore of a greatly reduced number of cope defects.

68. The weights of the various components on a single-arm strut molded horizontally are presented in Table 8. In the data, the approximate cost of removing the padded metal from both the main and intermediate struts also is given. A close scrutiny of the cost data will disclose that the cost of padding is significantly lower than that indicated by the totals. The figures include, in addition to the cost of the actual padding itself, the removal of unpadded metal, *i.e.*, that metal commonly designated as machining allowance. The figures unfortunately include the cost of counter-boring, an expensive and time-consuming operation requiring approximately 56 hr.

69. *Turbine Casings.* Casing design varies with nearly every turbine installation. Some new engineering findings or ideas are incorporated into each successive design. These, in turn, necessitate fitting changes in casing design. The designer's idea of what constitutes a fitting and proper design may or may not be in con-

Table 8

DATA ON SINGLE-ARM, HORIZONTALLY-MOLDED, STRUT

General Founding

Steel: Bw		Gating:	
Backing Sand: No. 4a	(Table 1)	Size—3 in.	
Facing Sand: No. 1d	(Table 1)	Type—Bottom	
Core Mix: Bottom Half: 2i	(Table 1)	Size of Risers:	
Upper Half: 2a	(Table 1)	3—18 x 8 x 13 in.	
		1—6 in. rd. x 13 in.	

Weight Distribution

	Weight, lb.	*Per Cent of Total Weight*		*Weight, lb.*	*Per Cent of Total Weight*
Casting with Gate and Risers Attached	5,988	100	Weight of Gate and Risers	1,750	29
Finish Machined	2,756	46	Metal Removed from Bore	1,482	25

Cost of Padding

Item	*Immediate Strut (Fig. 18)*	*Main Strut (Fig. 14)*
Metal	1482 x .01=14.82	4260 x .01 = 42.60
Heat Treatment	1482 x .01=14.82	4260 x .01 = 42.60
Burning		570 x .004= 2.28
Chipping		130 x .10 = 13.00
Rough Machining	1482 x .03=44.46	3560 x .03 =106.80
Total	$74.10	$207.28

formity with those basic foundry principles which govern the shape of castable structures. It eventually befalls the foundryman either to recommend a more castable design or to circumvent as best he can the disadvantage inherent in the design with sheer foundry technique.

70. Limitations of space prohibit extensive treatment of the manner in which troublesome points in casing design are solved. Briefly, in altering a design for founding, the fundamental considerations of efficient feeding and minimum internal stress, govern every single modification.

71. Efficiency of feeding is generally effected by padding every component in the cross section of the casting. Side walls, vertical spokes, bolt bosses, isolated pads, flanges within wall sections, and all similar regions of extra mass are thus treated. Occasionally there appears a design wherein a light section is located between two heavy thicknesses of metal. Thin sections of this kind which interfere with the proper feeding of other more massive sec-

tions below them, together with tie bars and long connecting members, are best left out to be subsequently welded in with the metallic arc. Flanges likewise are made separately and then attached to the casting by welding.

72. Sections which are beyond the reach of the main system of feed-heads—particularly those located on the bottom of the casting and attached on all sides to members of much smaller thickness—are best supplied with feed metal from "blind" or closed risers surmounted with whistler risers for the escape of air. Thick, flat areas of metal—entirely surrounded by sections of equal thickness but of lesser mass—are lightened to the weight of adjoining sections with a hole in their center. The practical handling of many of the foregoing points in design is illustrated in Figs. 21 to 28 inclusive.

73. The amount of padding applied to turbine casings varies from $\frac{1}{2}$ to $\frac{1}{4}$ in. per in., depending upon its relative position within the casting, its remoteness from the feed-head, and the height and angularity of section. Thorough x-raying of the casings (an average of 65 films per half casing) has shown that occasionally surprisingly thick pads are needed to eliminate all traces of center-line weakness. Padded metal is generally placed in those locations from which it can be most easily removed and on one side only, *i.e.*, either on the outside or on the inside, never on both (opposite) sides simultaneously. Inside padding is preferred to outside padding because it can be taken off more expeditiously. Manual chipping is employed for the removal of the latter; and mechanical boring, for the former. Occasionally outside padding lends itself to removal by machining.

74. As previously stated, the second fundamental consideration kept in mind when making changes in design is that of internal stresses. Internal stresses are fundamentally thermic in character and origin. Points on a casting between which dangerously high temperature differences might spring up are consequently vigilantly guarded against. Every design is carefully gone over for potential hot spots. The manner of their formation and elimination has already been related.

75. Hindered contraction stresses, too, are guarded against. Unlike the above, they have a mechanical genesis and act externally upon the casting. They are kept low in turbine molding by using

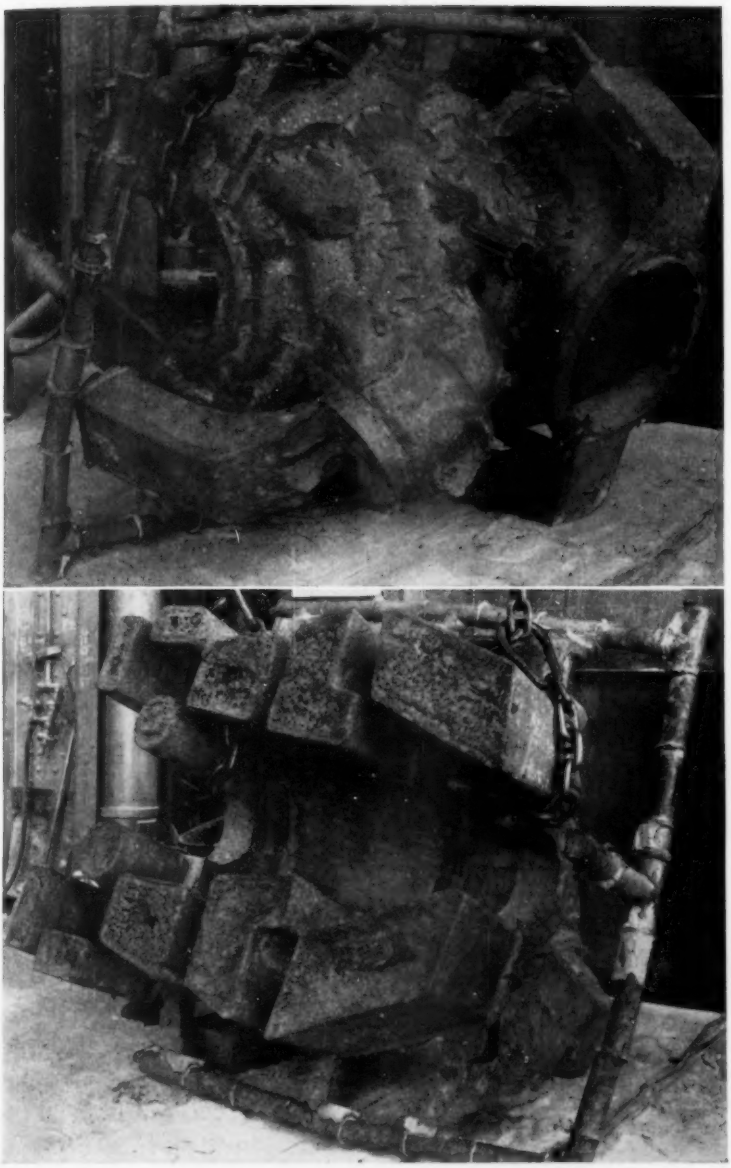


FIG. 21—TOP—I. P. TURBINE CASING, AS-CAST, OUTSIDE VIEW, SHOWING GATING, BLIND RISERS, AND OUTSIDE PADDING. BOTTOM—SAME, AS-CAST, INSIDE VIEW, SHOWING RISERS, GATES, AND PADDING IN BORE.

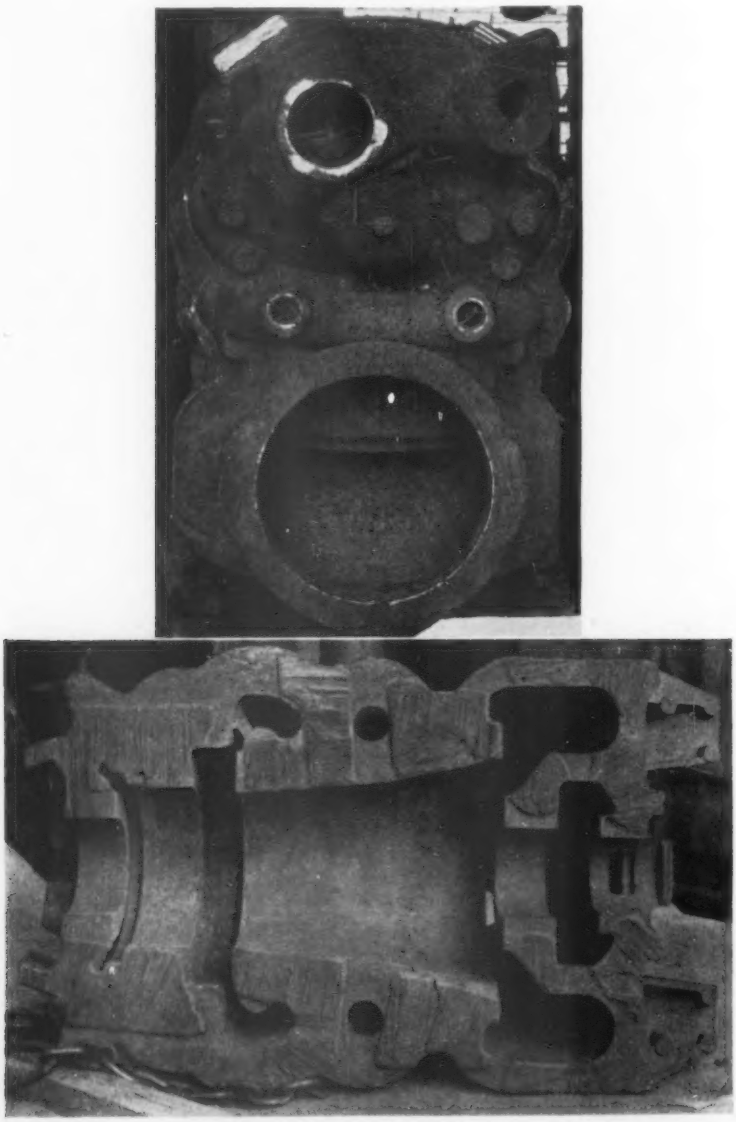


FIG. 22—TOP—I. P. TURBINE CASING, OUTSIDE VIEW, RISERS AND GATES BURNT OFF, SHOWING SOME EXTERNAL CHILLS AND HEAVY OUTSIDE PADDING ENDING AT THE WHITE CHALK LINE RUNNING ON EDGE OF BOLT FLANGE. BOTTOM—SAME CASING, INSIDE VIEW, WITH RISERS AND GATES BURNT OFF, SHOWING HEAVILY PADDED BORE.

green sand molds and collapsible cores. Turbine molds are faced with a layer of green sand 2-in. thick. The facing is hand-rammed; the backing up material is rammed with an air hammer. Six parting gates introduce the metal into the mold. Erosion of mold and core is prevented by nailing the facing with ½-in. diameter head nails at an average density of 1 nail per every 2 sq. in. mold surface. At the mouth of the gates, both core and mold are nailed with 3 nails per sq. in.

76. Collapsibility in the core is obtained by making it with a relatively thin exterior shell (approximately 4 in. thick), with a hollow center, and a cast iron arbor so constructed that it can be easily broken when desired. (Fig. 23.) The four cross bars connecting the main branches in the arbor are broken approximately 20 min. after pouring. Summing up, it is stated that the principal reason why turbine casings and other complicated castings have not cracked by hot tearing is the fact that they have been made in green sand.

77. By actual measurement, temperature gradients of approximately 1200-1300°F. have been detected in some of the subject casings. A study of the photographs in Figs. 21 to 28 will disclose that all the practices for the control of the direction of freezing which have so far been described were used on the casing, namely: slow introduction of metal (obtained by dividing the entering metal among 6 gates); parting gates; massive, trough-like feeding heads; heat insulating of risers; padding; and chilling.

78. Table 9 gives quantitative information on various phases of founding the pictured casing.

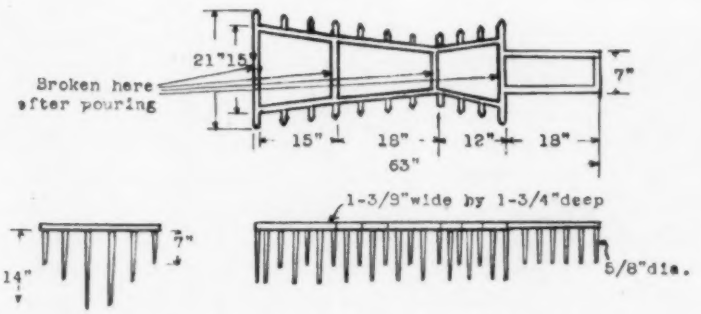


FIG. 23—CAST IRON ARBOR USED IN MAIN CORE OF TURBINE CASING.

Table 9

QUANTITATIVE INFORMATION ON FOUNDING OF TURBINE CASINGS

Foundry Data

Facing Sand	No. 1d (Table 1)
Backing Sand	No. 4a (Table 1)
Core Mix	No. 7d* (Table 1)
Size of Ingate	3-in. (6 in all)
Pouring Nozzle	2½-in.
Rate of Metal Rise in Mold	0.7-in. per sec. (average)
Steel Grade	C-Mo

Weight Distribution

Casing Weight, with Gates, Risers and Padding	10,153 lb.
Gates and Risers	3,968 lb.
Outside Padding	320 lb.
Metal Removed from Bore	1,570 lb.
Rough Machined, Including Weldments	4,680 lb.
Weldments	385 lb.

Heat Treatment

	Annealing (before chipping and machining)		*Stress Relieving (after all welding)*
	1	2	
Upheat	6 hr.	4 hr.	4 hr.
Hold	8 hr.	8 hr.	8 hr.
Temp.	1750°F.	1650°F.	1250°F.
Cool.	FC	FC	FC

*Pressure equalizing chamber and steam bleeder belt cores were made from Mix No. 5e (Table 1).

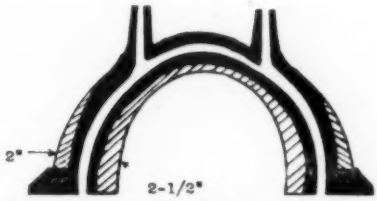


FIG. 24—SECTION THROUGH STEAM BLEEDER BELT. CROSS-HATCHING IS PADDING.

79. Using the above materials and practice, the cost per lb. of the finished casting was 87 cents. This figure covers costs of pattern, castings, rough machining, testing, and radiographing.

Throttle-Valve Body—Illustrating Control by Sectioning

80. The phenomenal strides which welding technology has been making for the past several years have won for it a permanent place in nearly all the metal working industries. Conservative designers and engineers are acknowledging it to be an invaluable tool, not only for minor repairs of surface defects but for the construction of metal assemblies. There is now scarcely a single steel foundry without a weldery.

81. Not infrequently, the foundryman is asked to cast a structure whose design defies every attempt to control the direction of its solidification. Throttle-valve bodies are an outstanding example of such a design. Since the chemistry of the castings mentioned herein is one which lends itself quite readily to welding, the most economical method, and sometimes the only method, whereby a sound condition of structure can be obtained in these complicated designs, is to dissect them into several more simple and elementary sections, cast each individually, and then unite them with welding. This is precisely what was done to the throttle-valve shown in Fig. 29.

82. It is seen that all the steam inlets were cast separately. The front and back plates, seats, brackets, and nipples were cut from C-Mo plating. Regarding the body proper, it was made solid by means of 4 parting gates, 130 lb. of outside padding (Fig. 30), and 8 bulky risers (6x10x11-in.) covered with head liquidizer compound. Hot tearing was avoided by making the body and its component parts in green sand molds and using cores made from oil sand topped off with green steel facing sand. Fig. 29-Top and Center shows the extent of heading and padding respectively.

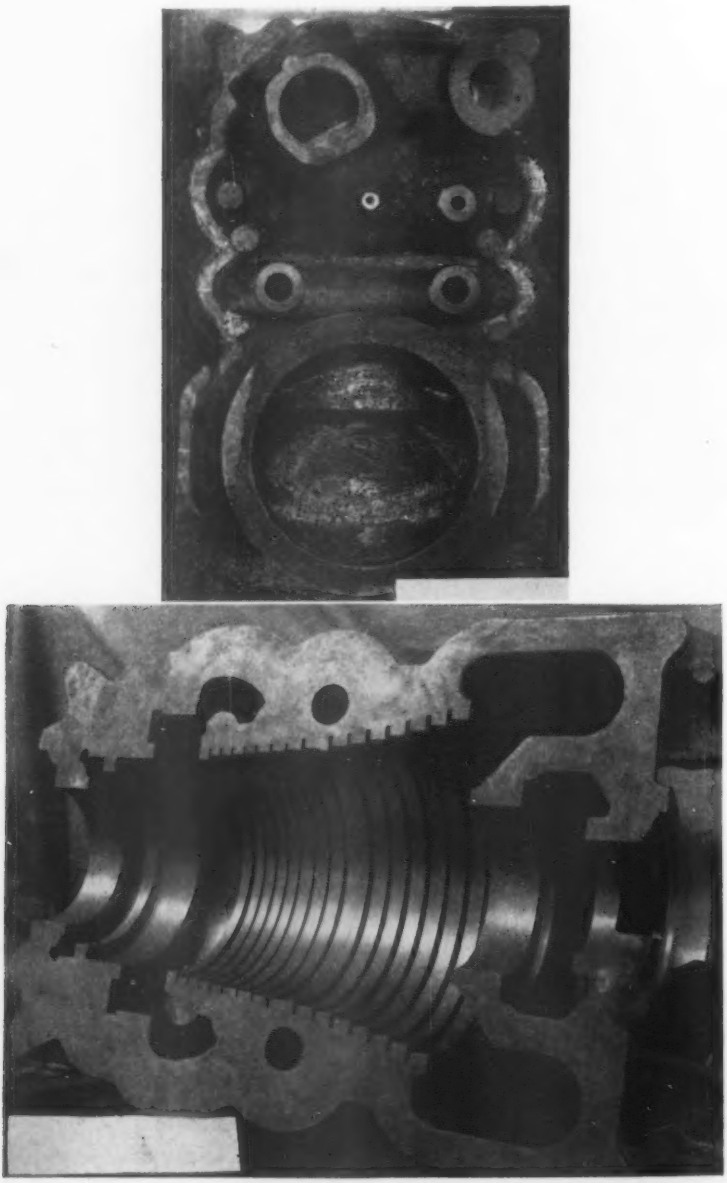


FIG. 25—TOP—I. P. TURBINE CASING, OUTSIDE VIEW, WITH PADDING REMOVED. THE WIDTH OF THE BOLT FLANGE SHOWS THAT APPROXIMATELY 2-IN. OF PADDED METAL HAS BEEN CHIPPED OFF. BOTTOM—SAME CASING, INSIDE VIEW, WITH ALL THE INSIDE PADDING REMOVED. THE STEAM BLEEDER BELT HOLE IS A GOOD LANDMARK WHEREBY TO GAUGE THE EXTENT OF INSIDE PADDING.

FIG. 26—I. P. TURBINE CASING, OUTSIDE VIEW, SHOWING WELDED ATTACHMENTS, NIPPLES, BRACES, FLANGES, PLATES.

83. Welding was performed in the flat position using $\frac{3}{16}$ and ¼-in. diameter electrodes and 300-500°F. of oxyacetylene preheat. Joints were veed to a 45° bevel with a root spacing of ¼-in. and were backed up with a machined backing ring. Deposition was effected layerwise, using a weaving technique. The branches were welded in position one at a time. All welded joints were then x-rayed for soundness and the entire weldment stress relieved at 1250°F.

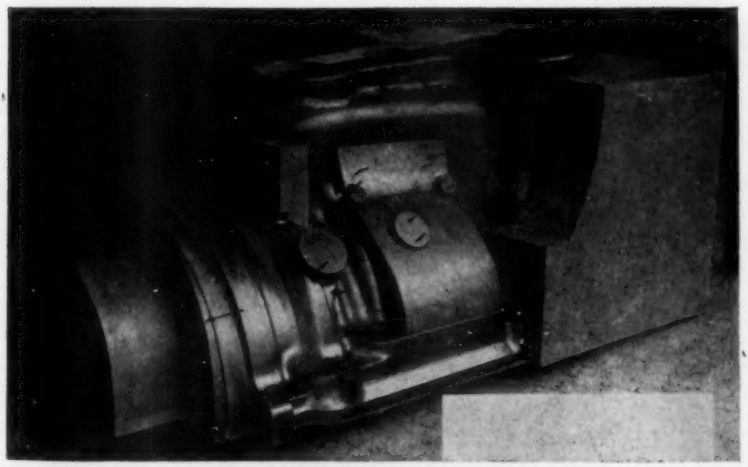


FIG. 27—PATTERN FOR H. P. TURBINE CASING, UPPER HALF, SHOWING OTHER INTERESTING POINTS IN DESIGN. ARROWS POINT TO PADDING.

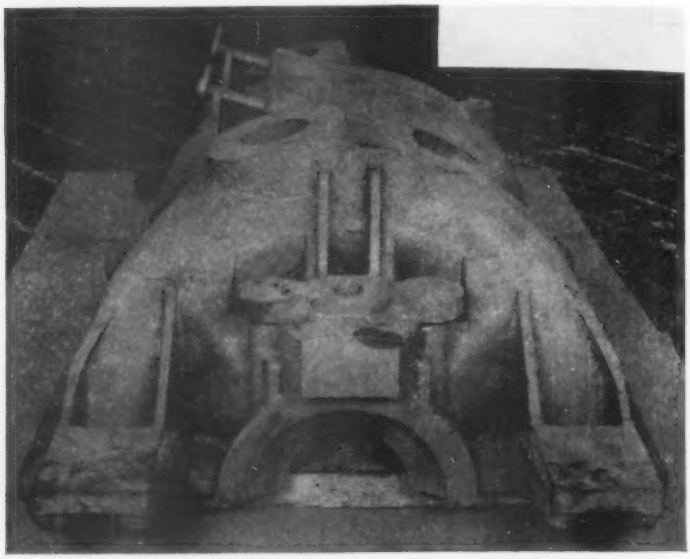


FIG. 28—I. P. TURBINE CASING, LOWER HALF, SHOWING END LIGHTENING HOLES CUT IN SOLID CASTING AND VARIOUS WELD ATTACHMENTS.

84. The molding materials and the amount of metal used in the various components of this structure are shown in Table 10.

85. Latest practice has succeeded in making sound throttle valve bodies with some of the branches integrally attached to the body. The throttle valve of Fig. 31 was made in such a manner. It is apparent that only half of the branches, *i. e.*, either all the upper or all the lower flanged sections, are integrally castable. The flanged sections were made in the cope. The T-shaped bosses, which are evident in the picture were made to provide a seat for subsequent weld attachments. Integral castings cost approximately $125.00 to $150.00 less, and can be made in approximately 2 weeks less time than those put together by welding.

86. Other important castings, which are being cast in sections and welded together into composite structures, are certain types of turbine casings and possibly lower turret track ring sections. Thermit welding is being contemplated as a method for joining the latter.

Turret Track Ring Sections

87. Turret track ring sections have been made solid by apply-

Table 10

DATA ON THROTTLE-VALVE BODY CASTING

Molding Materials							
Facing Sand	Nos.	1c, 1d	(Table 1)				
Backing Sand	No.	4a	(Table 1)				
Cores							
Upper Halves	No.	1d	(Table 1)				
Lower Halves	No.	7d	(Table 1)				

		Weight Distribution	
Weight of Body, with Risers and Gates	3,198 lb.	Outside Padding	130 lb.
Weight of Finished Body	1,688 lb.	Weight of Components, Branches, etc	1,177 lb.
Risers and Gates	1,440 lb.	Entire Welded Assembly	2,865 lb.

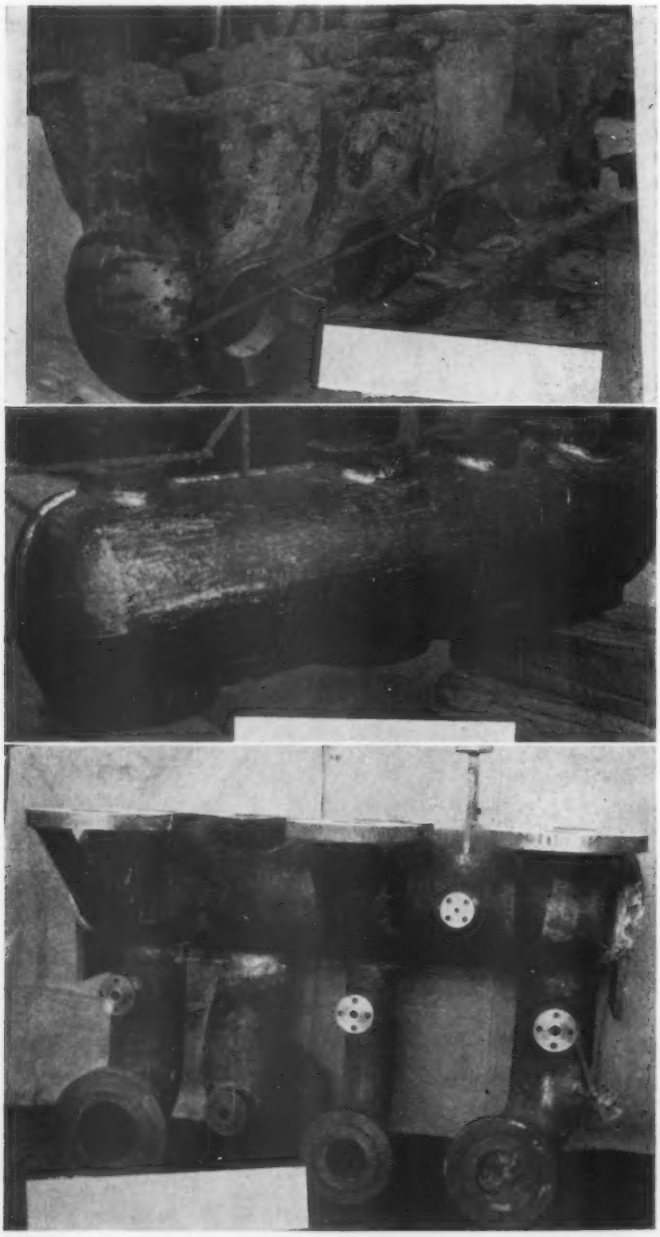


FIG. 29—TOP—C-Mo THROTTLE VALVE BODY, AS-CAST, SHOWING PARTING, MULTIPLE GATES AND RISERS. CENTER—SAME CASTING WITH RISERS AND GATES BURNT OFF. BOTTOM SIDE FACING FRONT. NOTE PADDING STARTING FROM ZERO ON BOTTOM AND RUNNING ¾-IN. DEEP AT MIDDLE (PARTING LINE). PADDING ON OPPOSITE SIDES RUNS SLIGHTLY OVER AN INCH DEEP. BOTTOM—C-Mo THROTTLE VALVE BODY SHOWING WELDED ASSEMBLY.

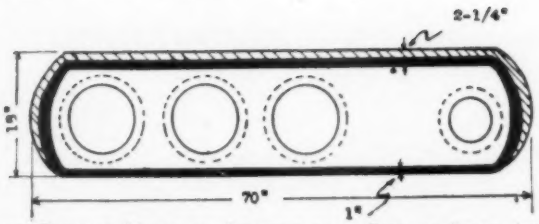


FIG. 30—SECTION THROUGH MIDDLE OF THROTTLE VALVE BODY AT RIGHT ANGLES TO THE HOLES. CROSS-HATCHING IS PADDING.

ing directional solidification principles to them in the manner illustrated in Figs. 32 and 33. Careful study of the casting will identify the following points of practice as being instrumental in obtaining the desired temperature gradient:

1. Positioning the lighter portion (the face) of the track in the bottom of the mold and the more massive parts directly over it.
2. Chilling the bottom corner sections with chill nails (3 per sq. in. and extending into the mold cavity 2 in.).
3. Denser nailing of the bottom surfaces of both core and mold.
4. Light padding on one of the upper vertical members.
5. The employment of massive risers and the top-pouring of same.
6. Step gating—though not used on the section pictured in the photograph—is being contemplated for use on subsequent castings.

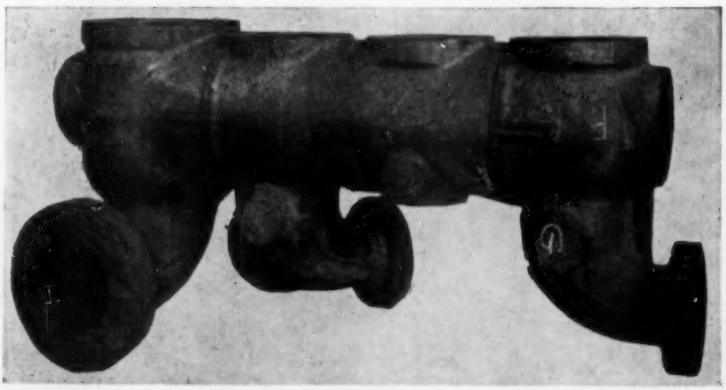


FIG. 31—THROTTLE VALVE CASING SHOWING CASTING WITH INTEGRALLY ATTACHED BRANCHES.

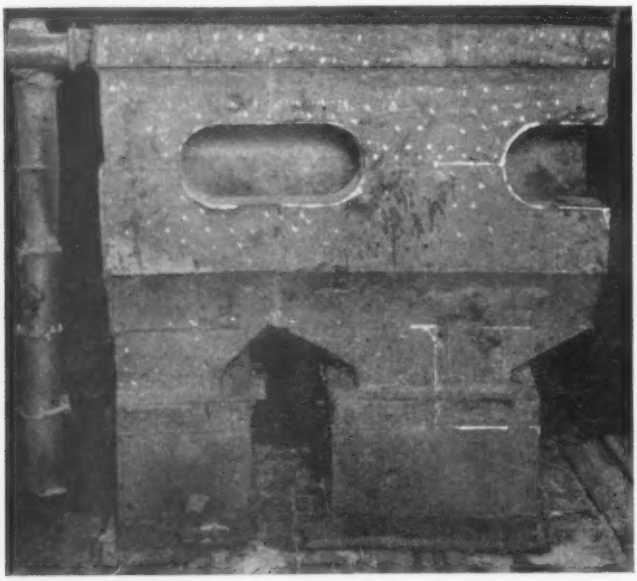


FIG. 32—SECTION OF TURRET TRACK, AS-CAST, WITH RISERS AND GATES ATTACHED.

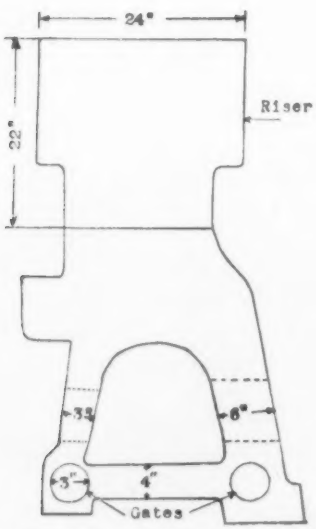


FIG. 33—FRONT VIEW OF TRACK SECTION.

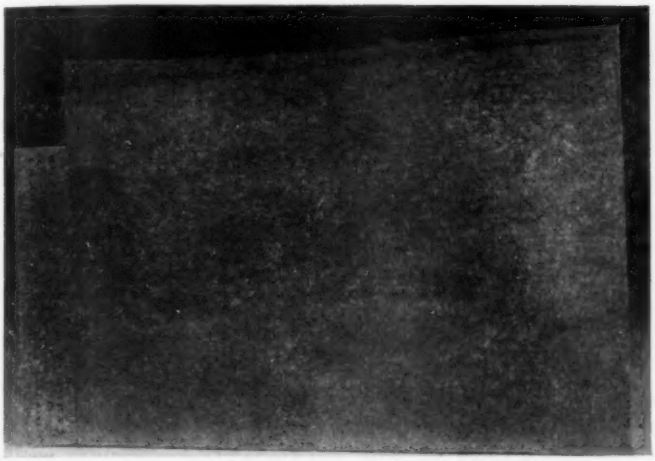


FIG. 34—SECTION CUT FROM FACE OF TRACK. NOTE DEPTH OF CHILL AND SOLIDITY OF METAL. STRUCTURE IN THE PHOTOMICROGRAPH IS AT 100X.

88. Fig. 34 shows the tight texture and compactness of metal obtainable with the above practice. Fig. 35 shows a micrograph of metal in the section. Both the mold and all cores were made of sandblast sand No. 5c mix (Table 1).

Controlling the Direction of Freezing with Preheating of the Cope

89. Because of certain practical difficulties, the use of preheating on the cope to retard the chilling of feed-heads, and thus increase feeding efficiency, has not been tried on any large casting. It is mentioned in this discussion as a possible method, for it is not entirely impracticable, providing the proper facilities are available.

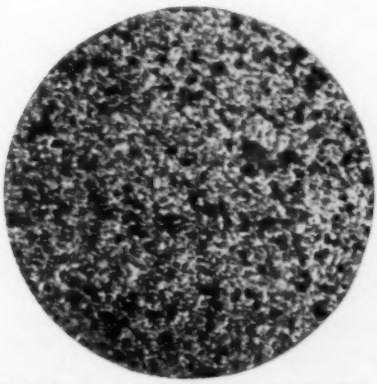


FIG. 35—MICROGRAPH OF SPECIMEN FROM TRACK RING CASTING.

90. In conclusion, it is stated that much has been done to obtain sound castings. There remain, however, many refinements to be made. Quantitative information is needed regarding the amount of padding and the size of external and internal chills to be used.

Appendix I

An examination of the data contained in Table 1 discloses the following facts:

Green Sand

(a) Air drying increases the permeability as well as the compression and shear strength of green molding sands.

(b) Air drying for periods in excess of 60 hr. affects disadvantageously their physical properties. Skin drying with a gas torch, however, nullifies the deteriorating effects of setting or drying time. Specimens air dried for 120 hr. and then torch dried, have physical values equal to those dried for 1 hr. at 225°F.

(c) Spraying the molds with molasses water for the preservation of the surface does not deleteriously affect the molds. Permeability, or the ability of a mold to vent its gases, is lowered by approximately 6 to 8 per cent.

Dry Sand

(a) Drying at 500°F. is productive of the highest physical properties in the sand.

(b) At least an 8-hr. sojourn at the drying temperature is required for good results.

(c) Washing the molds with silica wash exerts a pronounced choking effect upon their permeability. Breathing efficiency is lowered by approximately 60 per cent.

(d) Dry molds deteriorate rapidly if allowed to set too long (24 hr. and over). Their compressive and shear strengths are reduced 50 per cent or more.

Cores

(a) A temperature of approximately 450°F. appears to be best for baking cores.

(b) Spraying cores with linseed oil tends to increase their physical properties without adversely affecting their permeability.

(c) Washing cores with silica wash destroys their permeability.

(d) Prolonged exposure to air, of sandblast sand cores, after baking, does not damage physical properties. Exposure of No. 60 oil sand cores, however, is accompanied by slight impairment of physical properties.

Summary

The most outstanding findings discovered by the above tests are:

(a) Dry steel facing sands deteriorate rapidly with setting or prolonged exposure to air. This is the principal reason for the failure and burning down of the cope in anchor shank and anchor crown molds. Dry sand molds should be poured within 12 to 24 hr. after drying.

(b) Green sand molds do not deteriorate with time providing their surface is stabilized by torch drying before closing-up.

(c) Silica mold and core washes are to be used lightly and as sparingly as possible. They choke up cores and molds and thus obstruct the expulsion of whatever gases are generated within them.

(d) Spraying green sand molds with molasses water, and cores with linseed oil, does not harm either the physical properties or permeability.

Bibliography

1. Briggs, C. W., *"The Strength and Ductility of Steel Castings at Hot Tearing Temperatures,"* N.R.L. Report No. M-1479, Sept. 22, 1938.

2. Gagnebin, A. P., *"The Effect of Deoxidation Treatments on the Ductility of Cast Steels,"* TRANSACTIONS, American Foundrymen's Association, vol. 46, pp. 133-162 (1938).

3. McKnight, Jr., Charles, Discussion on paper by F. T. Sisco, *"Electric Furnace Steel,"* A.S.S.T., vol. 8, Dec. 1925.

4. Briggs, C. W., and Gezelius, R. A., *"Studies on Solidification and Contraction in Steel Castings—III,—The Rate of Skin Formation,"* TRANSACTIONS, American Foundrymen's Association, vol. 43, pp. 274-302 (1935).

5. Heuvers, A., *"Was hat der Stahlgieber dem Konstruktem uber Lunker-und Ribbildung zu sagen?"* STAHL UND EISEN, no. 35, 1929.

6. Batty, George, JOURNAL, American Society of Naval Engineers, February, 1934.

7. Briggs, C. W., Gezelius, R. A., and Donaldson, R. A., JOURNAL, American Society of Naval Engineers, May, 1938.

DISCUSSION

Presiding: F. A. MELMOTH, Detroit Steel Castings Co., Detroit, Mich.

C. W. BRIGGS[1] *(Written Discussion):* I compliment the authors on their fine paper and for explaining the methods of manufacture of large Navy steel castings. It is certainly interesting to note the manner in which fundamental information on the solidification of steel castings has been used.

There are many commendable practices illustrated in the paper. One of the most interesting is the use of models of the proposed casting to study the casting design and the planning of gating, heading and the application of padding. The use of cast-weld construction is also commendable in producing directional solidification and prevention of hot tearing.

The only main point to which exception can be taken is the statement in paragraph 2 of the paper which claims that "Perfectly sound castings are rare." I believe that the authors' work with large complicated miscellaneous castings has led them to forget the numerous production castings of carefully planned design being manufactured by the industry, such as certain railroad and automobile castings which are readily produced sound in all sections. Many of these castings are designed to fulfill the conditions of controlled directional solidification.

Of course, the oxidizing slag shown in Table 2 is not entirely of the best practice. The CaO content is entirely too low and the SiO_2 too high for a good dephosphorizing slag. Of course, this may not be necessary in this particular case since, judging from the phosphorus analysis at melt-down, it was not necessary that phosphorus be eliminated. The high MgO content, however, shows that an undue errosion of the furnace bottom has taken place. A CaO content of approximately 40 per cent and SiO_2 of about 13 per cent would produce a better oxidizing basic slag.

These items, however, do not detract from the excellence of the paper and the description of the application of controlled directional solidification to large steel castings.

T. D. WEST[2] *(Written Discussion):* The authors are to be complimented on this extremely intelligent paper on directional solidification.

[1] Technical Adviser, Steel Founders' Society of America, Cleveland, O.
[2] Foundry Superintendent, Symington Gould Co., Rochester, N. Y.

This paper is of the type that the Navy has been releasing in the last number of years for all foundrymen concerned to digest.

Too much attention can not be paid to the fine thought of the use of a model before going ahead with a similar job as described in this article. There is only one draw back and that depends on the size of the casting to be made. That is, if the cost of manufacturing of the model and casting can be accepted in the price of the job. The writer has yet to see anyone who can read a blueprint and tell where all the hot spots, so to speak, are located and be able to correct these by proper application of directional solidification. The model certainly lends aid to this factor and should be considered when one is considering such jobs as are shown in the series of photographs in this paper.

In Table 1, mix No. 1-G is room air dried for 120 hours. This mix contains approximately 9 per cent bentonite and 3.5 per cent water. The writer would question the spalling effect of such a long drying time. Are the molds dried open or closed? We in our plant noticed considerable amount of spalling effect or erosion when any mold is allowed to remain open any length of time at the above mentioned moisture content. We tend to close all our green sand molds as soon as is convenient to do so. Would not also such a long air dry period tend to set up more hindered contraction which we of today are trying to reduce to a minimum?

The authors speak of the scabbing effect of slow pouring in paragraph 34. Exact causes of scabbing of molds are not definite because of the variance of the following list pertaining to it. Scabs may be caused by unevenness of ramming, permeability, moisture, or contraction or expansion of the sands by heat from the molten metal. Due to the fact that so many variables are present in scabbing, it is hard to apply the cause to one thing alone.

The writer is pleased to note that internal chills are used on the stockless anchors, one of the many castings acceptable to the Navy. The foundryman, as a rule, uses internal chills on all regular class of commercial castings of today. However, where specifications are changed regarding the use of such, the product can be nearly always made by adhering to those principles. The price will vary however, with the amount of inspection necessary. No job is too difficult if the foundryman can correct or suggest a change in design to get the most from directional solidification.

The authors in describing their multiple gating, state that the metal runs down the banks of the mold in quiet, and smoothly descending streams. Anyone who has ever stood on top of a mold and watched metal flow into a mold from a multiple gate will see the metal from the gates, except the one gate at the bottom, surge in and drop to the bottom of the mold. The writer has tried all sorts of devices such as varying the diameters of gates and the steps and also making the step gate going into castings at an angle to secure smoother functioning

of the step gate. Have the authors anything to add to the method of step gating large castings?

Attention should be called to difference of heads as shown in Fig. 21 and Fig. 14. The heads on the latter certainly must have to be 100 per cent efficient. The saying goes that the heads by weight only have to feed about 3 to 5 per cent shrinkage on a casting and anything over that is superfluous.

The authors cover their risers with anti-piping material to retard their cooling. This then lets the atmospheric pressure work on the head or riser pushing liquid metal down into the mold with the aid of gravity. The writer has found by using more of these prepared riser dusts smaller heads giving bigger yields can be used in the steel foundry. This allows a very cheap element, atmospheric pressure, to do an efficient job of feeding castings. In Fig. 21, the casting shows the use of blind risers. The writer has found, by placing a flat core over the entire top of the head coated by a heavy wash of thermit, the feeding of this riser becomes very efficient. This then tends to act as an open riser with riser dust on it and also takes advantage of atmospheric pressure. This thermit must be so placed as not to be touched off until the head is filled.

The authors state that the cost of the finished casting was 87 cents per pound. This certainly is not a complete cost. Did this include overhead, depreciation and taxes?

The writer would also like to question the statement of the author about spraying the molds with molasses water. We have experienced quite a dampness pick-up on all molds sprayed with molasses water, dried and closed for a time of 8 to 10 hours before pouring. We have discontinued the practice and are using a silica-flour wash even though some permeability is sacrificed as this seems to draw the minimum amount of dampness.

J. H. HALL:[3] For the past year or two, I have been familiar with the practice of making a great many of these castings Mr. Brinson describes. I noticed there was a difference in the height of the heads between some of these pictures. For instance, in Fig. 19, the heads are filled up good and full, but in Fig. 14 where a strut is shown, the ratio of the height of the head to that of the castings is much less than in the other illustrations and much less than what I am familiar with in struts made in other foundries.

The history of controlled directional solidification in this industry goes back farther than most of us here appreciate. About 1907 Henry M. Howe and Bradley Stoughton worked out proper methods of pouring sound ingots and published an important article* before the American

---

[3] Consulting Engineer, Philadelphia, Pa.

* Howe, H. M., and Stoughton, Bradley, "*Influence of Conditions of Casting on Piping and Segregation, as Shown by Means of Wax Ingots*," TRANSACTIONS, A.I.M.E. Vol. XXXVIII, p. 109. See also, Howe, H. M., "*Piping and Segregation in Steel Ingots*," TRANSACTIONS A.I.M.E. Vol. XXXVII, p. 72.

Institute of Mining & Metallurgical Engineers on the subject. To the best of my recollection, almost every principle which is now advocated under the name of controlled directional solidification was explained in that article.

H. H. BLOSJO[4]: There is one thing I would like to take exception to and that is in the summary under item (c) relative to silica washes destroying the permeability. That may be true in a sense that it does destroy the surface permeability. In our shop we want to do this. This permeability to us is not desirable. It does not destroy the permeability of the core as a whole, and the gases formed within the core expel themselves from the mold through the permeability of the core and such vents as are added to the core. Surely it is not desirable for this gas to penetrate the surface of the core into the metal. Nor is it at all desirable for air or gases in the mold to find their way out of the mold through the core. This can be taken care of by venting the mold.

MR. BRINSON: Several questions have been raised here. The first was raised by Mr. Briggs, that it is hard to get an absolutely solid or perfect casting. In view of our radiography, and we have been radiographing castings in the foundry for ten years, and from that inspection and other inspections for the Navy standard of work, a perfect casting means just that, "a perfect casting." Sometimes we chip out spots in a casting about as big as the head of a pin and weld them. Another thing you will realize is, producing a casting that you can put into production, and producing the type of casting that your produce in the jobbing shop, where every casting is different, is an entirely different proposition.

We have found in connection with models, as discussed by Mr. West, that on a job of this kind, the models pay for themselves before the patterns leave the pattern shop. In other words, on a big job, where you have a big pattern and a number of core boxes worked on simultaneously by several men, in such a case the model will pay for itself in the pattern shop in making up the patterns and the core boxes. It further pays for itself in setting the cores and the chipping necessary in the foundry.

Another question was raised about scabbing due to slow pouring. The scabbing that we have reference to is the burning down. Especially in a heavy mold with a very heavy section, which has a flat cope, if it is poured too slowly, the heat from the steel will burn down the cope unless it is fairly well reinforced. With a heavy section casting, it is better to pour a little faster to keep the cope from burning down. In the case of these turbine cases where you can see the metal poured into the molds, I have noticed a dozen of them poured and I have as yet, with this multiple gating system, to see any one poured where the metal went in with enough force to hit the core. In the case of the struts with stepped gates, we start with a certain size section gate at the bottom, use a little larger one in the middle, and a still larger one up at the top, often angling them up. I have watched those castings poured and

[4] Metallurgist, Minneapolis Electric Steel Castings, Minneapolis, Minn.

watched the metal come into the bottom gate until the metal got pretty well up to the middle gate. Then it came into the middle gate until it got to the top, and then started at the top gate.

In connection with the risers on the strut castings, I think it is shown as 20-in. high. There is a very heavy continuous riser around the periphery of the barrel and we find the feeding goes down pretty far but does not go down into the casting. If we had found it had, we would have put a higher riser on there, but we got by with this riser satisfactorily.

As to the question raised about the use of internal chills, as I stated, on the turbine casing, there were some internal chills on the bottom of the flange. On the low pressure castings, the Navy went from the cast steel casings to the built-up welded casings and back to the cast steel casings. On these, no internal or external chills whatever were used. So there are no internal chills or chaplets used on any of the later turbine castings. We go to a great deal of trouble to keep from using chaplets, especially on high pressure work.

Regarding the question raised about washing the core, probably the wrong word was used there, but I believe we will all agree that washing cores and molds with silica wash does *impair* permeability rather than destroy. The purpose of the wash is to give a smoother finish on the casting and that will close the permeability somewhat. However, you can make a core so tight that the metal will not lay to it. Most of the cores we make for valves are hollow cores. Still we do not like to have the surface too close. We like to have it close enough to get a smooth casting but not too close. If it is to be machined, it does not make any difference if it is a little rough. It is better to have it rough and solid rather than have it too close and have blow holes.

In connection with the cores, we got into the turbine casing business because of the insistence of the Navy on such rigid specifications that the commercial field became a little frightened. A number of years ago, the Navy put out turbine castings on bids. The prices they got on those turbine castings ranged from $3.75 to $4.25 a pound for rough machined castings. They wired us to submit an estimate. We submitted an estimate which closely approached $2.00 a pound for a rough machined casting, and we figured that we would have to make five castings to get a good one. Then we started to apply this padding and the controlled directional solidification of the casting, or the wedging of the casting. What we tried to do was to make the design approach a wedge as far as possible, small at the bottom and big at the top, cold at the bottom and hot at the top. When we got through, I wish to state that, so far as the foundry was concerned, the cost of the castings was just about 30 per cent of what we estimated, and we turned a considerable sum back to the Navy Department. Since that time, we have gradually brought the price of the castings down until we got an order for some low pressure castings, in which the cost of the castings, shipping and the casting put in the machine shop, got down to between 12 and 13 cents per pound, which is reasonable for turbine casings.

The Heat Treatment of Malleable Iron

By R. J. Cowan*, Toledo, Ohio.

Abstract

The heat treatments of pearlitic malleable irons has been of great interest. As one of the author's contribution to the literature on this subject, in this paper, he outlines the results obtained by subjecting pearlitic malleable iron used for commercial camshafts to an austempering treatment and shows the results micrographically. He points out that by carefully regulating the temperature of the quenching bath and the time of immersion, it is possible to control the hardness desired. Pearlitic malleable irons thus treated are said to possess superior wear-resisting characteristics.

1. Malleable iron is a material which owes its malleability to an extended period of heat treatment. When first cast, it contains approximately 2.5 per cent carbon, entirely in the combined form so that the metal is extremely hard and brittle. During heat treatment, this combined carbon is reduced by a process of graphitization until, in the fully-annealed casting, but very little if any combined carbon remains. The carbon in fully-annealed castings exists as free carbon or graphite of distinctive form. Industry is becoming increasingly aware of the fact, that the heat treatment of a high carbon material of this kind, can be modified to produce a great variety of materials which will have, in their various modifications, a wide range of physical properties. The vast extent of this field may be indicated when it is recalled that the common steels are classified on the basis of their carbon contents and owe their many uses to the specific properties that may be developed by heat treatment.

2. There are today a rapidly increasing number of uses for these materials. Certain kinds have been extensively developed for

* Surface Combustion Corp.

Note: This paper was presented at a Malleable Session of the 44th A.F.A. Convention, May 7, 1940, Chicago, Ill.

particular purposes, and these are finding wide acceptance among various users. Other materials are being developed and, without doubt, will find a place in suitable applications. It is the purpose of this paper to call attention to some of the things that have been done and to suggest other fields of development that appear promising.

THE FIELD OF PEARLITIC MALLEABLE IRONS

3. It is customary in the manufacture of certain types of pearlitic malleables to modify the usual annealing treatment to produce the type of material desired. This consists, as a rule, of changing the treatment during the second stage annealing operation. It is assumed that all are familiar with the usual type annealing cycle which embraces a first stage treatment at high temperature and a second stage cooling to complete the cycle. The pearlitic material is removed from the furnace after the completion of first stage annealing, and after cooling is then subjected to a special treatment at or below the critical temperature range for a period of time sufficient to obtain the special properties desired in the metal. As a rule, it is possible, by means of a microscopic examination of the metallographic structures obtained, to identify those, that experience has shown, will produce the desired physical characteristics. Certain of these structures will be presented and discussed in this paper.

4. Fig. 1—Top shows the microstructure of a camshaft, taken from commercial production, which has a structure that is said to be suitable for this work. This reveals a background of carbide structure with temper carbon nodules dispersed throughout. Around each of these nodules, there appears a white area in which the carbon is lower than in the body of the metal. It has been found to be desirable to limit this white area to very small regions and perferably to eliminate it entirely. Experience has shown that a pronounced white area around these nodules affects the machineability of the metal and makes it more difficult to cut. This would be especially true in the case of a metal having the structure shown in Fig. 1—Bottom. Here the carbon nodule is surrounded by a considerable area of metal that is practically carbon-free. This affects machineability adversely.

5. A close examination of the metal, shown in Fig. 1—Top, reveals that the carbide constituent in this case is very largely

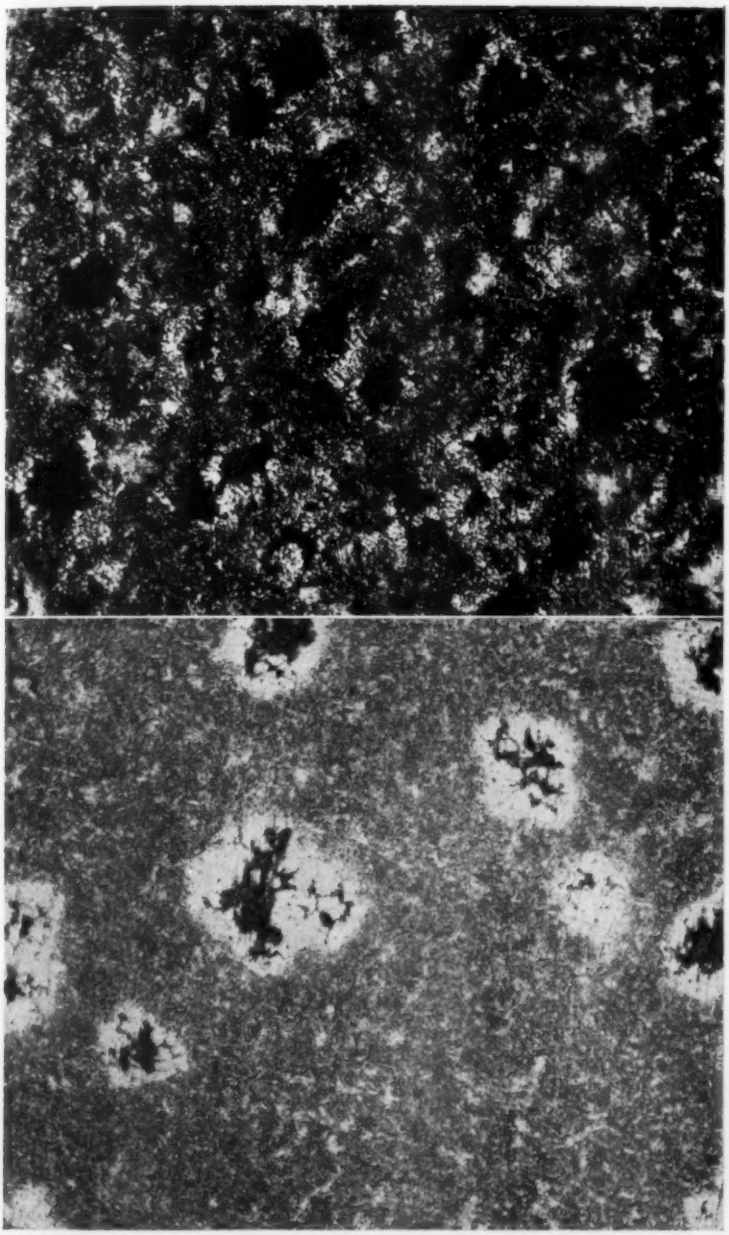


FIG. 1—TOP—DESIRED STRUCTURE OF COMMERCIAL CAMSHAFT OF PEARLITIC MALLEABLE IRON, x100. BOTTOM—UNDESIRABLE STRUCTURE IN PEARLITIC MALLEABLE IRON CAMSHAFT. x100.

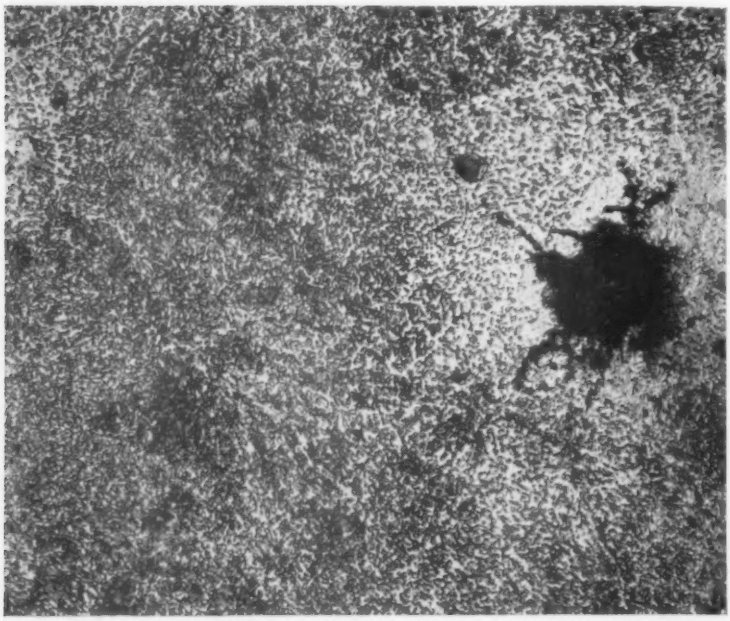


FIG. 2—SAME AS FIG. 1 BUT AT X500.

spheroidized. Fig. 2 shows this more clearly, since it is the same metal taken at high magnification. This shows that the white areas, which surround the carbon nodules, are not in this case wholly devoid of carbon as they are in Fig. 1—Bottom, since it may be seen that they contain spheroids, although in lesser amount than the rest of the structure. There is an advantage that comes from having the carbide in the form of spheroids when the metal is to be subjected to heat treatment, because, in this form, it will dissolve most readily when heated to temperatures suitable for hardening. This will be referred to later.

6. When a metal of this type is hardened by quenching from a high temperature, the structure becomes quite different in appearance under the microscope. This is shown in Fig. 3—Top, which has been obtained by quenching from high temperature in water. The details of this structure are more clearly shown in Fig. 3—Bottom, which is the same piece under a still higher magnification.

7. Attention is called to the fact that spheroids of carbide are still present in the hardened structure. These may be clearly distinguished by a careful examination of the micrographs, especially

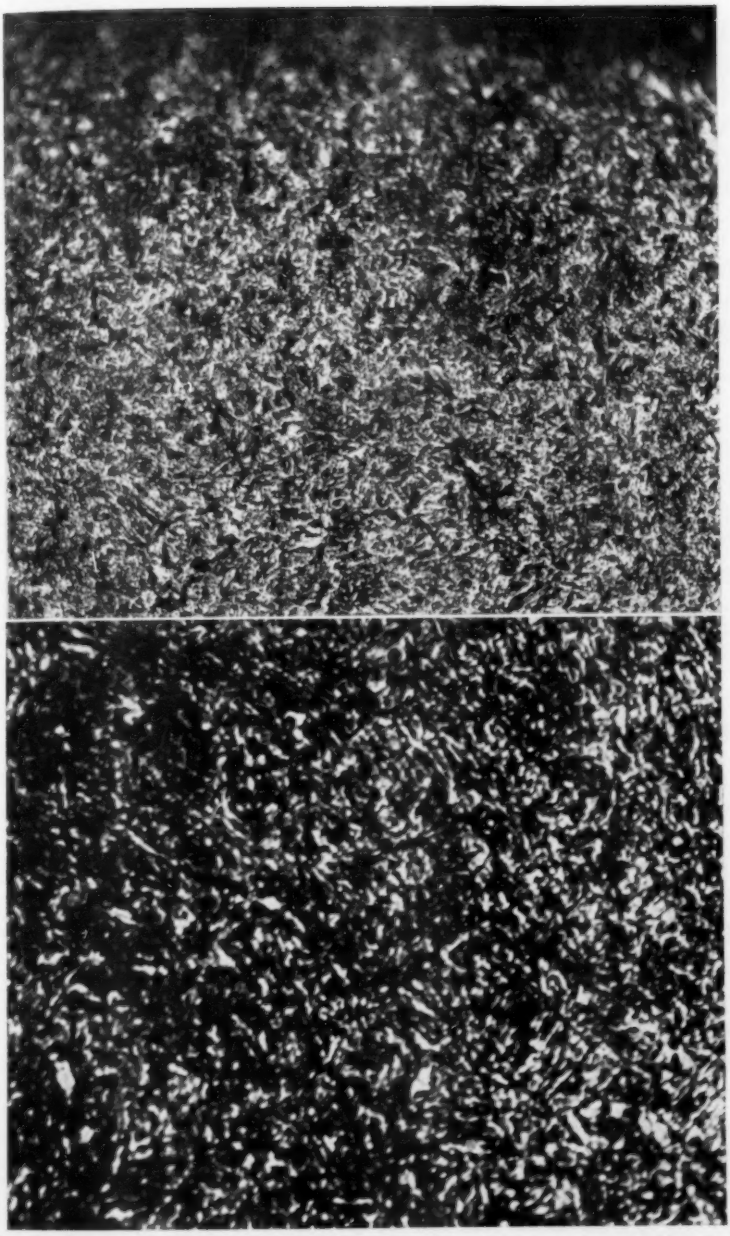


FIG. 3—TOP—STRUCTURE OF PEARLITIC MALLEABLE IRON CAMSHAFT WHICH HAS BEEN HARDENED BY QUENCHING FROM A HIGH TEMPERATURE IN WATER. x500. BOTTOM—SAME AS FIG. 3 BUT AT x1000.

Fig. 3—Bottom. Experience in other fields has indicated that a structure of this type has superior wearing qualities. The presence of these spheroids which, of themselves, are extremely hard, embedded in a hardened steel structure, represents a type of structure which has been proved to provide the very best wear-resisting surfaces in many different kinds of operations.

8. In certain applications where resistance to shock is a big factor, it has been found that the presence of spheroids of carbide in the case hardened structure is the type that will give the best service under these trying conditions.

THE HARDENING OPERATIONS

9. To develop a wear-resisting surface, it is necessary to heat the metal to a temperature where the carbon will be brought into solution in the iron in sufficient amounts to provide hardening when quenched in water or oil, the procedure in this respect being similar to that used in the hardening of steel. The abundance of carbides in the pearlitic malleable structure are not all required to provide the necessary degree of hardness. Consequently, it is not necessary to hold this material at high temperature for a long time to insure the solution of sufficient carbides to provide the requisite hardness. The excess carbides, when present as spheroids, impart wear-resistance in the manner described.

10. Recent studies of the hardening operation with high carbon steels of various types have brought forth a method of procedure that is considerably different from that of the usual operation. Instead of quenching directly into cold water or oil, the metal is quenched from the hardening temperature into a liquid bath that is maintained at a definite temperature. It has been found by this procedure that definite holding times are necessary to accomplish the full degree of hardening that is possible at each temperature. In this way, a definite hardness can be obtained by maintaining the required temperature for a definite time. Furthermore, the hardness is found to vary with the temperature of the quenching bath, the high hardness values being obtained by a long hold at compartively low temperatures. This process is known as "austempering," when applied to steel, and has received a great deal of attention and publicity during the past year.

11. The results obtained are considerably different from those of the usual quench and draw method heretofore employed. By the

earlier method of procedure, the steel was quenched in cold or warm quenching media, which produced a drastic hardening which was too great for most applications, so it was necessary to reheat and hold for some time at a low temperature to relieve this condition and obtain the desired degree of hardness. The results obtained by the austempering method show a type of hardness that combines a certain degree of toughness without brittleness and, accordingly, seems to possess certain inherent elements of superiority. This method is being used in a number of industrial applications.

12. Some bars of iron were subjected to a heat treatment of this kind to observe the results obtained. Bars of hard iron were given an annealing treatment sufficient to complete first stage annealing. They were then quenched from this temperature in a bath of molten lead which was held at various temperatures. Fig. 4—Top shows the results obtained by holding for one hour at a temperature of 1000°F. The hardness was found to be 40 Rockwell C.

13. Attention is called particularly to the number of carbide spheroids in this structure. Fig. 4—Bottom shows this structure at high magnification. The portion of the micrograph that is out of focus is a nodule of temper carbon. It is photographed in this way to show the complete absence of a white ferritic area at this point and also the fully hardened structure that covers the entire specimen.

14. A greater degree of hardness can be obtained by quenching in lead that is held at a lower temperature. In Fig. 5—Top is shown the results obtained when the metal is quenched at a temperature of 650°F. and held at this temperature for one hour. The details of this structure are shown more clearly at high magnification in Fig. 5—Bottom. The hardness was found to be Rockwell C 49. Close examination of this microstructure indicates that spheroids of carbide are still found to be present within the hardened structures.

15. These results are sufficient to illustrate the possibilities of a heat treatment of this kind. Intermediate values may be obtained by holding at intermediate temperatures. There is no danger of holding too long a time at temperature since it has been found that the structure corresponding to that temperature is

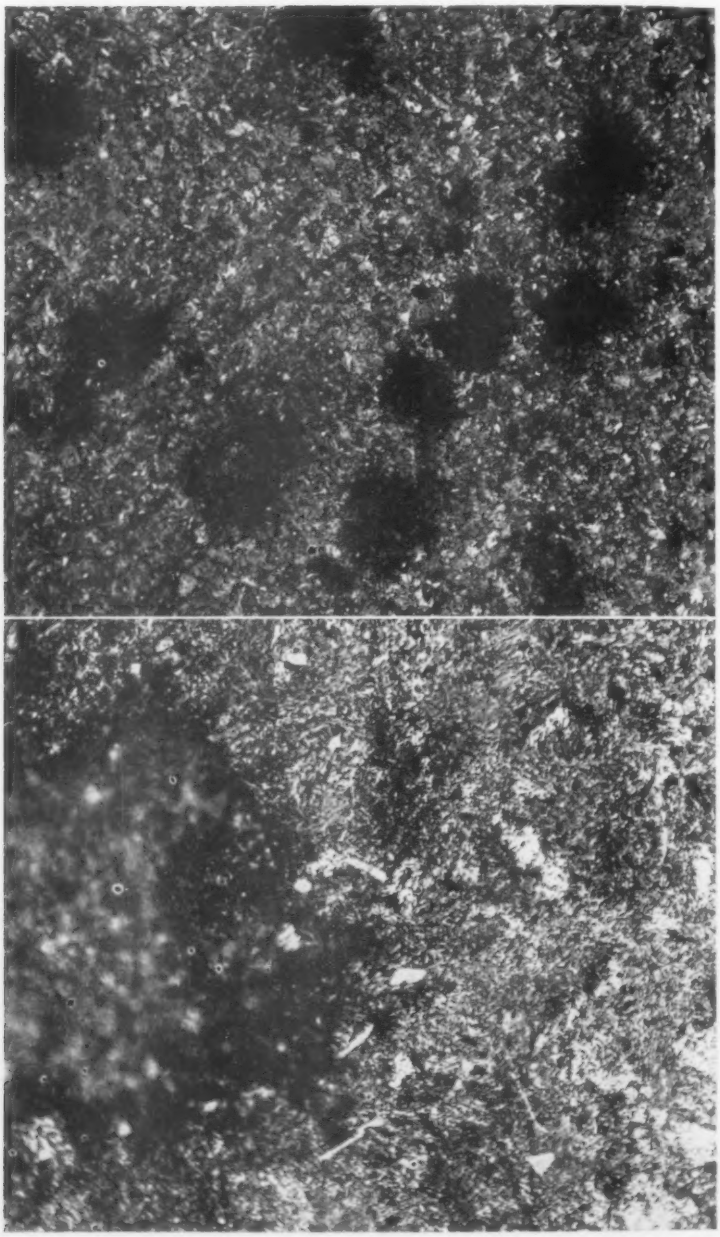


FIG. 4—STRUCTURE OF A PEARLITIC MALLEABLE IRON WHICH WAS HEATED AT AN ANNEALING TEMPERATURE SUFFICIENT TO COMPLETE THE FIRST STAGE ANNEALING AND THEN QUENCHED IN A LEAD BATH AT 1000°F. FOR ONE HOUR. BOTTOM—SAME AS FIG. 4 BUT AT X500.

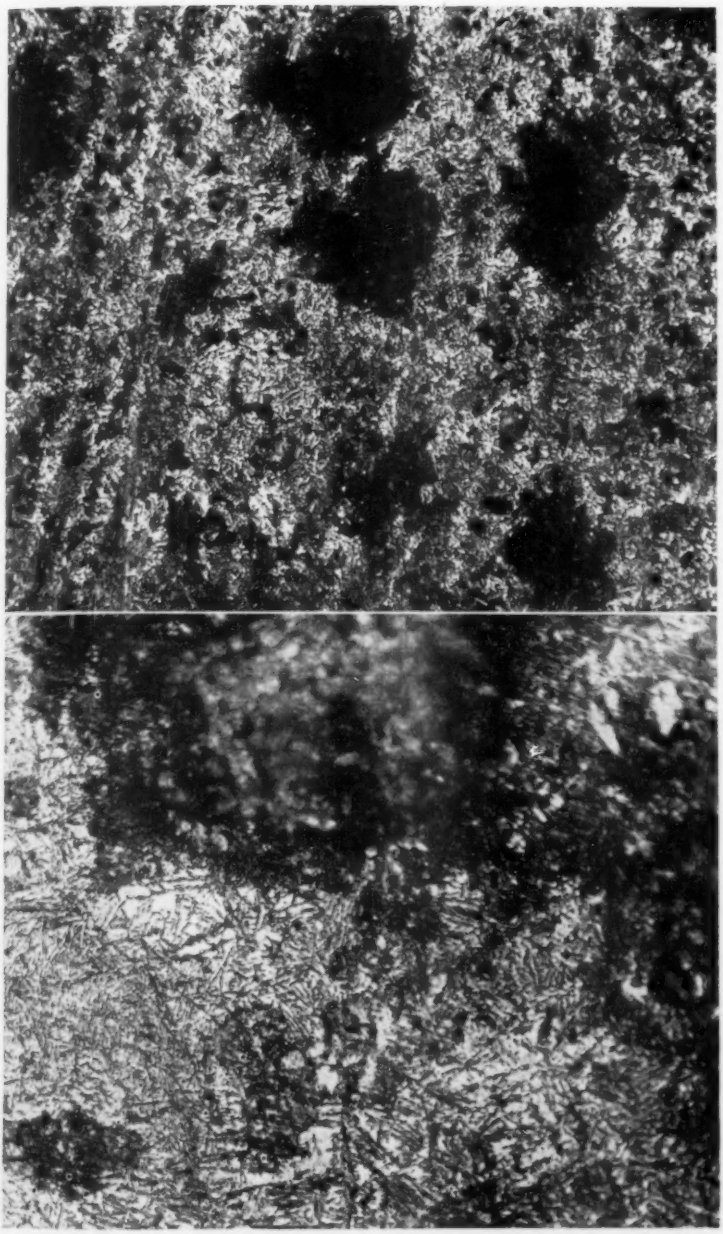


FIG. 5—SAME METAL AS IN FIG. 4 BUT QUENCHED IN LEAD AT 650°F. FOR ONE HOUR. BOTTOM—SAME AS FIG. 5 BUT AT X500.

reasonably constant after it has once been obtained. The only limitation is that of a minimum time which must in all cases be exceeded to obtain full transformation.

SUMMARY

16. Based on the results of the present investigation, it may be stated that:

1. A method of heat treatment is proposed which may be suitable for the processing of certain machine parts.

2. Constant hardness values may be obtained that depend only on a definite temperature control of a quenching bath.

3. An ideal type of structure is obtained in this manner which will possess superior wearing characteristics.

4. Proceeding in this manner, a hardened structure may be confined to the surface areas of a heavy section while the remainder of the piece will receive a heat treatment that will have a toughening effect.

DISCUSSION

Presiding: R. J. ANDERSON, Belle City Malleable Co., Racine, Wis.

R. J. COWAN: In the hardening of a high carbon steel, it has been customary to quench from a high temperature, but when quenching from this hardening temperature as it is called, in oil or water, the brittleness is too great. There is hardness there but also brittleness. Therefore, to obtain the desired ductility, the sample is given a drawing operation; that is, it is heated to a low temperature and held for a time to reduce the extreme brittleness and give some ductility to the hardened part. That is the old, well-established practice of harden and draw. This austempering process gets away from the draw idea and modifies the quenching practice, quenching from the same temperature, but instead of quenching in oil or water, quenching the specimen into a lead bath or a salt bath which is held at a definite temperature and holding it in that lead bath for a definite period of time.

There is no danger, as I understand it, of holding too long. There is a danger of not holding long enough, so that when the specimen is quenched from this hardening temperature in the lead bath, a definite hardness will result. However, with heavier sections, there is a progressive effect from the outside in, that is, it will be very hard on the outside which decreases gradually toward the core where there will be a very tough structure. The advantage of that procedure is that it gives a structure that is not only hard but very tough.

The question in my mind, and which I tried to deal with in this paper, was whether or not this austempering idea might be utilized in certain hardening operations in these special heat treated malleables. I have completed in my laboratory, although I was not able to get it in time for this paper, some work where I treated a section of metal that was 1½-in. in diameter and quenched it in lead and obtained, by scratch hardness, a variable hardness from the extreme hardness at the surface to a very tough core.

H. L. WALKER[1] *(Written Discussion):* Mr. Cowan has discussed the possibility of using a constant sub-critical temperature for quenching malleable iron products and has pointed out that the method has many possibilities for the improvement of certain properties, depending upon the application to which the iron is to be used. I believe that the malleable iron industry will find this method of heat treatment of ever increasing importance and that we may expect to hear a great deal more about it in the future. Some of the possibilities of this type of heat treatment have been investigated by C. S. Nielsen* in the metallurgical laboratories of the University of Illinois by an application of the isothermal transformation of austenite to the spheroidization of pearlitic malleable iron.

The usual commercial cycle for spheroidization is approximately as follows:

1. Anneal white iron at a temperature of 1720°F. for about 24 hours to convert it to a mixture of temper carbon and austenite.

2. Air quench the iron through the critical range to establish a fine laminated pearlite. Upon reaching a temperature of about 1100°F. the iron is reheated as in step 3.

3. Reheat to 1280°F. and hold at the temperature for 36 hours to produce a spheroidized condition.

Mr. Nielsen's investigation revealed that, when step 2 as outlined above is replaced by an isothermal quench at 900°F. or below, the time required for the spheroidization anneal in step 3 can be lowered to 5 hours with good properties resulting from the heat treatment.

The investigation was conducted upon 1 and 1½-in. round bars of white cast iron prepared in an air furnace and partly malleableized by annealing at a temperature of 1720°F. for 24 hours to convert the white iron to temper carbon and austenite. Upon cooling, the austenite was in the vicinity of the eutectoid composition.

---

[1] Professor, Department of Mining and Metallurgical Engineering, University of Illinois, Urbana, Ill.

* Metallurgist, George D. Roper Corporation, Rockford, Illinois.

The analysis of the iron used was as follows:

	Per cent
Total Carbon	2.19
Silicon	1.10
Manganese	0.94
Sulphur	0.08
Phosphorous	0.15

The rate of austenite transformation was determined by quenching the iron from a temperature of 1600°F. through a series of lead baths at constant sub-critical temperatures. The rate of transformation for the particular iron used is presented in Fig. 6 where temperature of quenching is plotted against time on the logarithmic scale. Curve *ABC* in Fig. 6 represents the length of time required for the beginning of austenite transformation, and curve *DEF* represents the length of time required for completion of austenite transformation, in the temperature interval of 650 to 1250°F.

The structures produced by quenching one-inch round bars from 1600°F. to various sub-critical temperatures and then annealing at 1280°F. are presented in Figs. 7 to 11. All specimens were etched in nital and photographed at a magnification of 1000 X. Temper carbon areas are not shown in the photomicrographs as the main interest was centered around spheroidization of cementite.

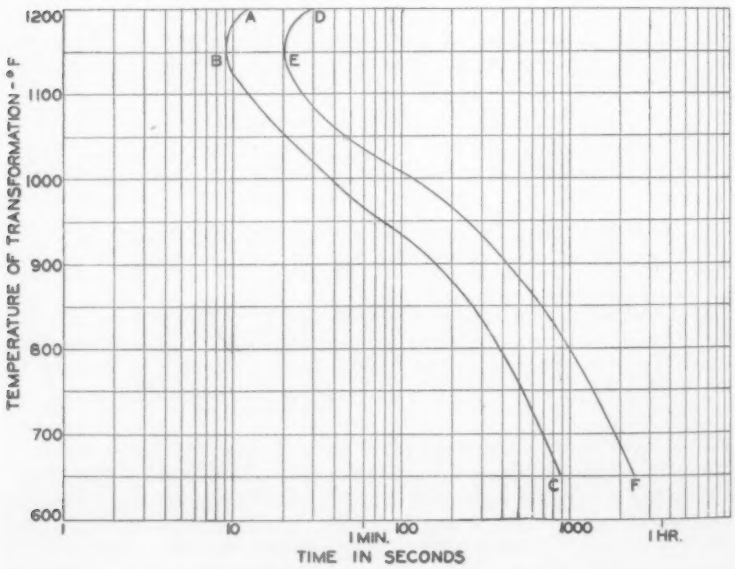
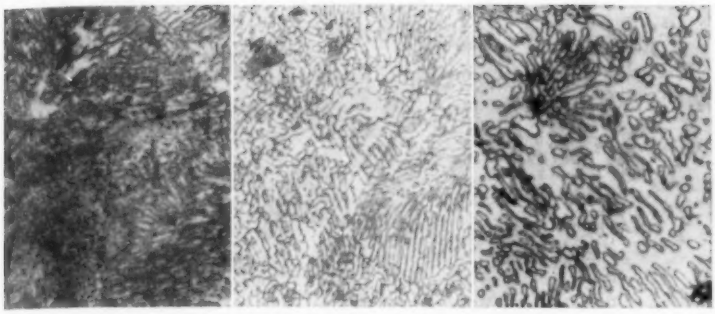
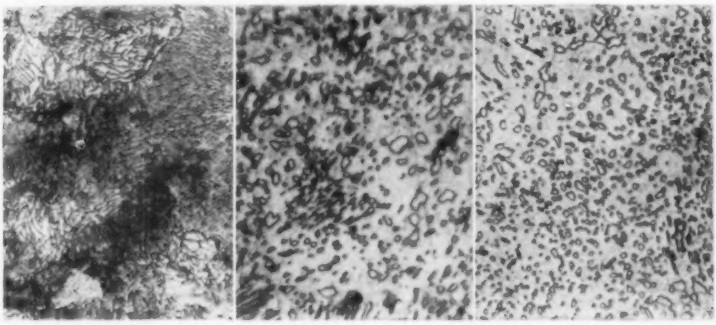


FIG. 6—RATE OF AUSTENITE TRANSFORMATION. QUENCHING TEMPERATURE PLOTTED AGAINST TIME. CURVE ABC — TIME REQUIRED FOR BEGINNING OF TRANSFORMATION. CURVE DEF — TIME REQUIRED FOR COMPLETION OF TRANSFORMATION.



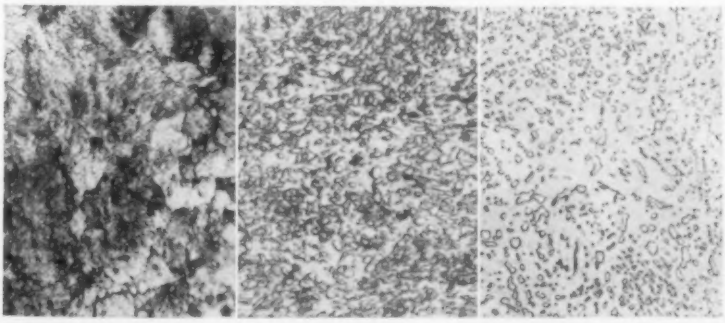
(A) (B) (C)

FIG. 7—STRUCTURES PRODUCED BY AIR COOLING FROM 1600°F. X1000. A — NOT ANNEALED. B — ANNEALED FOR 5 HOURS AT 1280°F. C — ANNEALED FOR 24 HOURS AT 1280°F.



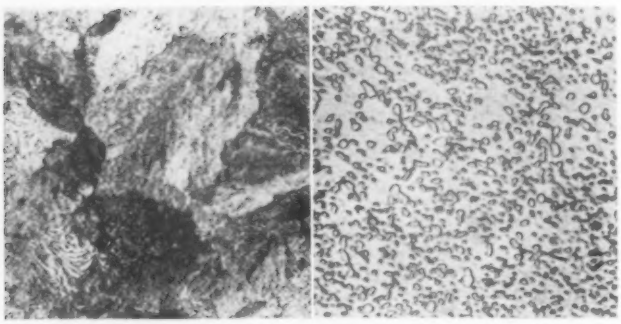
(A) (B) (C)

FIG. 8—STRUCTURES PRODUCED BY QUENCHING FROM 1600 TO 1100°F. IN LEAD BATH. X1000. A — NOT ANNEALED. B — ANNEALED 15 HOURS AT 1280°F. C — ANNEALED 24 HOURS AT 1280°F.



(A) (B) (C)

FIG. 9—STRUCTURES PRODUCED BY QUENCHING FROM 1600 TO 1000°F. X1000. A — NOT ANNEALED. B — ANNEALED FOR 5 HOURS AT 1280°F. C — ANNEALED 24 HOURS AT 1280°F.



(A) (B)

FIG. 10—STRUCTURES PRODUCED BY QUENCHING FROM 1600 TO 900°F. X1000. A — NOT ANNEALED. B — ANNEALED 5 HOURS AT 1280°F.

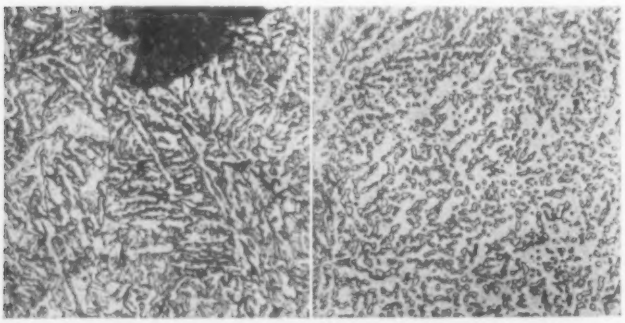
The properties developed in bars air-cooled from 1600°F. and spheroidized, compared to the properties of the bars quenched from 1600 to 800°F. and spheroidized, are tabulated below.

Bars air-cooled from 1600°F. and annealed for 36 hours at 1280°F. (Average of 2 bars.)

Elongation in 2 inches, per cent	9.01
Tensile Strength, lb. per sq. in.	81,300
Rockwell B Hardness	84

Bars quenched from 1600 to 800°F. and annealed for 15 hours at 1280°F. (Average of 2 bars.)

Elongation in 2 inches, per cent	8.01
Tensile Strength, lb. per sq. in.	90,400
Rockwell B Hardness	90



(A) (B)

FIG. 11—STRUCTURES PRODUCED BY QUENCHING FROM 1600 TO 800°F. X1000. A — NOT ANNEALED. B — ANNEALED 5 HOURS AT 1280°F.

To prove the worth of such heat treatments for commercial usage will require a detailed study of the physical properties developed for a great number of possible combinations of heat treatment; and a study is needed of the specimen size limitation to which the heat treatments may be applied. Such studies are being extended at the University, and a detailed report of the work will be made in the future.

C. F. JOSEPH:[2] In regard to this austempering, we have done some work along that line but we have not been able to get any better physical properties than if we just quench in air and draw back. For instance, we have taken some regular pearlitic malleable, quenched in air from 1600°F. and drawn back at 700°F. and we would get about the same ultimate strength, elastic limit and elongation as though we quenched in a lead bath at 1000°F. We have found that it is necessary to quench into a bath at a higher temperature than the one at which one draws back if quenching in air, but the physical properties obtained do not seem to check with what is obtained in steel, where the austempering gives a tougher material. I imagine that a higher elongation should be obtained.

According to the work that Mr. Cowan has done, he thought he should get higher elongation by the austempering, and I believe in steel they do. The austempering gives a tougher material, especially in the thinner steel parts. In fact, I have been told that if spring steel is quenched in lead it can be tied into a knot. In work that we have done on pearlitic malleable, that has not shown up. That might be due to the fact that the sections are heavier than has been the case on steel. The author mentioned doing some work on a 1½-in. cross sectional area. There is a possibility that perhaps by the addition of some alloy, the austempering might show up better than it does on plain iron. In steel they have found by the addition of a certain alloy—whether it was chromium or some other alloying element I do not recall,—but the addition of some alloy has brought out the improvement in the physical properties whereby the elongation has been increased.

MR. COWAN: Mr. Joseph, how would you change the hardness by a drawing operation?

C. F. JOSEPH: Usually by either increasing the time or temperature at draw.

MR. COWAN: The matter of time and temperature are the important considerations and that is a reheating operation. Compare that with the austempering operation, which is a simple matter of maintaining the hardening bath at one temperature to obtain a definite result. Just how far that goes in making a pearlitic like an austempered steel remains to be seen. This is only an opening wedge suggesting there is an effect that ought to have a very important bearing.

Another thing that interested me is that with that kind of structure,

[2] Metallurgist, Saginaw Malleable Iron Div., General Motors Corp., Saginaw, Mich.

we also obtained the spheroids in the hardened matrix, which seemed to me to be a very important item.

The relative values of these two methods certainly are not answered in this paper but they are worthy of further study and consideration. Austempering is a simple operation of holding at a definite quenching temperature to obtain a very definite result, and the result obtained is dependent on the temperature at which it is held.

H. BORNSTEIN:[3] Mr. Cowan rather over-emphasizes the simplicity of this operation. It is a lot more difficult, on a commercial scale, to austemper than it is to quench and draw, because in the quench and draw operation the quenching can be done in an oil or a water bath, then taken out and put it in a draw furnace, which is an air draw. In austempering, quenching is done in a medium which should be held at a fairly high temperature and that means a salt bath. It is more difficult to work with a salt bath than it is with an oil quench or a water quench.

Furthermore, you can quench a piece of steel or a casting in a very short time in a water, oil or air quench. It is a matter of seconds or minutes at the most. With austempering as we know it, it is a matter of a good deal longer time, an hour or two hours; perhaps, for heavy section castings, it may take days to complete the austempering operation. So it involves much larger and much more expensive equipment.

MEMBER: The author said this material has superior wearing qualities, yet the Rockwell figures quoted are not extremely high as compared with those the carburizing people quote. Does he have any figures as to how the 45 Rockwell C compares in wear resistance to, we will say, a 60 Rockwell C secured by carburizing?

MR. COWAN: Unfortunately, I do not have the figures that will show that, but I am taking the experience of a friend of mine who has turned his entire plant operation into a procedure of that kind. These spheroids are suspended in a hardening matrix and these spheroids of themselves are extremely hard. That is cementite, and they are held in position in a hardened matrix and, while it does not show up extremely hard under the usual hardness test, the hardness test is not everything in the way of determining wearability. In practical operations, these have been giving superior results, these spheroids that are held in position, so to speak, in a hardened steel matrix. In addition it is shock resisting. It not only stands up under wear but it has surprising shock resisting properties.

In reply to what Mr. Bornstein has pointed out, bear in mind that quench and draw involves an additional operation. It is quite true it does not take long to quench a sample in water or in oil, but after it is quenched it must be drawn which means it is reheated from the cold up to some temperature and held for a period of time, and that time is about as long as the austempering operation in many instances.

We know from Bain's curve, that when the lead bath is held at a

[3] Director of Laboratory, Deere & Co., Moline, Ill.

low temperature it will take a long time to get maximum hardness. This takes a period of hours, whereas if maximum hardness as measured by the Rockwell is not desired, a few minutes at a higher temperature will produce the effect.

C. F. JOSEPH: I want to stress what the author mentioned about Rockwell hardness for pearlitic malleable versus steel. A number of years ago when we first made cam shafts out of pearlitic iron, the various companies wanted a minimum Rockwell of 60, because that is what they thought they were getting on their steel cam shafts. We tried to get a minimum Rockwell of 60 and it was rather difficult. One can obtain a hardness of 59 to 62, but not every time. They started running tests with a Rockwell of 55 and they found that after a test of 25,000 to 50,000 miles, there was not a sign of wear. They then ran a test on cam shafts with a minimum Rockwell of 50 and over a period of miles there was no wear. They dropped the Rockwell to 45 and still there was no sign of wear. On the cams which were electrically hardened with the Tocco process there still was no sign of wear with a Rockwell of 45, and the last tests were run with a Rockwell as low as 42. Apparently pearlitic malleable at a much lower Rockwell hardness will not wear as readily as steel. That is due principally, or probably entirely, to these spheroids.

The same thing is true on rocker arm tests that have been conducted. The minimum hardness on a rocker arm made out of steel was usually 60 Rockwell and the same procedure had to be gone through on rocker arms, the 55 and then 50, and now the minimum requirement is a 50 Rockwell on rocker arms, and those also do not show any wear after years of running.

So that apparently, again, this pearlitic malleable material which is 45, 50, 55, or 60 Rockwell C does not show any wear compared to steel.

H. BORNSTEIN: These spheroids may be of great importance, but there is another thing which I think is of even greater importance, and that is the presence of the temper carbon in this material as an aid to wear. Along that line, I want to relate an experience with a cast crankshaft as against forged steel. In that case, we had a typical high strength gray iron structure in which we did not have these spheroids; yet the gray iron, at a lower hardness, gave better wear resistance than the forged steel at a higher hardness. I do not believe in that case it was a matter of spheroids at all. It was simply that in the cast material this graphite helped the wear resistance.

MR. COWAN: Mr. Bornstein, do you suppose that if you had more graphite nodules in there, you would have had still better results? Do you believe there is any relation between the number of nodules and the results obtained?

H. BORNSTEIN: I do not think you can speculate very much about wear. It does not work that way. We have done quite a lot of work on wear, on different materials and sometimes the facts conflict with your theories which must be modified accordingly. We do know this, that hard-

ness is no measure of wear. It may be true for a similar material, a similar composition, that as the hardness increases the wear resistance also increases. That is, a 0.90 per cent carbon steel of 600 Brinell might wear better than a steel with 200 Brinell or a 400 Brinell, but we have had steels with 0.90 per cent carbon and 200 Brinell that wore better than steels with 0.50 per cent carbon and 600 Brinell. In those cases, for abrasive wear, we found that the carbon content was of a great deal more importance than the hardness.

G. K. MINERT:[4] Could the author tell us something about the time of heating through the higher temperature for quenching. The reason I ask is that we have reheated spheroidized pearlitic materials and allowed them to cool in air and when we examined them under the microscope, there were very few spheroids left. The material was very finely divided, with some lamellar pearlite, but the structure more closely approached sorbite than spheroidized pearlite.

MR. COWAN: Undoubtedly that is affected by a great many different things. In the first place, it is affected by the condition of the spheroids in the raw material you are working with. Were the spheroids large or were they small? Were they well developed or were there a multitude of them? It seems to me that will affect the results. That certainly affects the result obtained in the time necessary in reheating because it is obvious that with a myriad of spheroids a short heating period will be sufficient to put those into solution, whereas with just a few larger spheroids in a similar area, it is going to take longer. The condition of the material in the first place has a lot to do with the time required to put it into solution. With very finely divided, very finely dispersed spheroids, the time is very short.

Mr. Joseph mentioned the Tocco hardening process, which is a matter of a few seconds-hardening. The same thing is found in flame hardening. It is just a matter of a very short hold at temperature. Certainly you do not get the interior of the metal hot enough to harden on quenching. It is just a surface differential heating. The period might extend from a few seconds to a few minutes, depending on the carbon condition of the original material.

MEMBER: In the early part of the paper, the author states that when the spheroids were closer to the temper carbon nodules, a more readily machinable material was produced than when the temper carbon nodule was surrounded by an area of more or less carbonless iron. The paper does not give much history on how those results were obtained.

MR. COWAN: I cannot give much of the history of that material because that material was taken from a shop. We took a sample of material that was exactly what we wanted for an ideal. Then we took a sample of material that could not be machined and was undesirable. Now, just how those two were produced, certainly, is the same procedure that causes a bull's-eye malleable, which is the wrong kind of treatment through the second stage annealing.

[4] Assistant Metallurgist, Gunite Foundries Corp., Rockford, Ill.

G. K. MINERT: Mr. Cowan, in that connection it might be well to point out that with sufficient graphitization retardant of some sort in the material, such as manganese, the spheroids will be close to the graphite. If they are absent, you will have a bull's-eye structure. That comes back primarily to reaction rates. Can the spheroidized structure be produced with the spheroids near the graphite, without having some retardant present?

MR. COWAN: The answer is yes. I wonder, if we line these phenomena up on the basis of critical points, if it does not come back fundamentally to the matter of reaction rates. If the critical point is changed by any kind of an alloy addition, the reaction rate on cooling would be changed. We might as well make an analysis of this matter from that standpoint.

G. K. MINERT: You speak of reaction rates but, for instance, what happens if the treatment is moved away from the critical? What happens if you get it close to the critical?

MR. COWAN: A change of temperature does not do anything more than change the size of the spheroids. If you come close to the critical in one case and in another case you are 50 degrees away from the critical, does that have any greater effect than changing the size of the spheroids? I have the idea that it is a change of the size of the spheroids; that if you come close to the critical you will have very finely dispersed spheroids, whereas you get farther away and they are larger in size. I do not know whether that is right or not.

H. BORNSTEIN: I think with the lower manganese, you perhaps have a material which is more sensitive to the formation of these ferrite particles around the graphite. You have to be more careful in the cooling cycle to produce a pearlitic malleable by cooling rapidly from the first stage graphitization temperature to draw temperature, say, from 1600 down to 1300°F. With rapid cooling an absence of the ferrite will be obtained, while with slower cooling you will get quite a formation of the ferrite. With enough manganese in there, the formation of that ferrite will be retarded.

C. F. JOSEPH: I believe that is true. Everybody knows that manganese helps to produce an iron which is freer from ferrite.

CHAIRMAN ANDERSON: How do you determine the difference in machinability of the various structures. You refer especially to a material that has ferrite around the graphite nodule as being a hard material to machine because the ferrite sticks to the tool tip. If that is the case, when you machine a pearlitic malleable that is entirely free from massive cementite, or free cementite, we expect and know that you will have difficulty in machining because you have an abrasive action that ruins the tool tip after a short period of time. If you have either the structure you described or lamellar pearlite that is entirely free of

any massive carbides, how would you account for the ferrite around the carbon nodules decreasing the machinability when you have as a comparison the malleable iron that is entirely ferritic?

MR. COWAN: I have nothing in the way of figures. That is a practical observation made by those who machine the metal. They say, "This machines well; give us this," and "This does not machine well," and, when examined under the microscope, it was found that there are these ferritic areas around the carbon nodules in those specimens that do not machine well. That is all relative, it is all comparative and depends on a great many factors, as you can see. But the test that I referred to was a practical machining test.

MR. COWAN *(Written Closure):* We are grateful indeed to Professor Walker for this fine contribution and are pleased to know that the University of Illinois is continuing its work along these lines. We will look forward in anticipation, for the report of this work.

The S-curve given in Fig. 6 is very interesting. It differs from the more familiar form which deals with the heat treatment of small sections of eutectoid steel. It is surprising to find that a characteristic effect is produced in such large sections by moving the curve to the right of its usual position. It should be observed that the microstructures resulting in this case are different from those found where quenching small sections of eutectoid steel in the same manner.

It is noted also that the size and distribution of the spheroids are traceable to the form of the carbon in the quenched specimens so that, the more nearly lamellar this form, the larger the spheroids and the longer the time required for their formation.

An examination of Fig. 11A reveals a number of spheroids of cementite occurring in the quenched specimen similar to those described in the paper.

Attention is called to the fact that the iron used by Mr. Nielsen has an unusually high manganese content. An increased amount of manganese is known to have a beneficial effect on the spheroidization of the usual iron so that it is necessary to consider this fact in studying the results obtained.

This contribution provides a valuable addenda to the paper and is greatly appreciated. We believe Professor Walker is right in saying that this field of heat treatment will become increasingly important.

Effects of Sulphur on Properties of Electric Furnace Cast Iron

By Fulton Holtby* and Ralph L. Dowdell*, Minneapolis, Minn.

Abstract

In this paper, the authors record the results of an investigation of the effects of sulphur on the various properties of electric furnace cast iron. Not only are data recorded but observations of the behavior of the molten metal prior to pouring also are given. After reviewing past investigations on the subject, the authors made 40 casts of electric furnace iron, under controlled conditions, in the form of various type test bars and tested them for transverse strength, deflection, tensile strength, flowability (fluidity), machinability, hardness, contraction, depth of chill, chemical analysis and microstructure. As a result of these investigations, the authors conclude that at about 0.18 per cent sulphur, there is a transition point in the properties of electric furnace cast iron. Up to that percentage, increased sulphur lowers transverse and tensile strengths and hardness and increases deflection and that at percentages above that figure, the reverse is true; that an increase in sulphur will decrease the resulting manganese analysis, the decrease being more rapid in iron containing more than 0.18 per cent sulphur; that flowability (fluidity) of the iron decreases rapidly at about 0.18 per cent sulphur, the fluidity remaining the same above and below this amount, provided manganese is held constant; that chill depth is not affected by sulphur, provided manganese content remains constant; and finally that up to 0.14 per per cent sulphur, machinability decreases, between 0.14 and 0.18 per cent sulphur, it increases and above the latter figure again decreases.

* Instructor, Foundry Practice and Professor of Metallography, respectively, University of Minnesota.

Note: This paper was presented at a Gray Iron Session of the 44th A.F.A. Convention, May 9, 1940, Chicago, Ill.

INTRODUCTION

1. In the past, foundrymen have endeavored to keep the sulphur content in cast iron below 0.10 per cent, believing that it was the source of innumerable undesirable properties. Few investigations have been conducted to determine whether or not the effects of sulphur were as bad as is generally believed. The purpose of the investigation, as discussed in this paper, is to determine the effects of sulphur on electric furnace cast iron.

REVIEW OF PREVIOUS INVESTIGATIONS

2. Sulphur in pig iron is derived primarily from the coke and sulphur compounds of the blast-furnace burden. The foundry grade of blast-furnace pig iron has a sulphur content of 0.02 to 0.05 per cent. Ordinarily, when metal is melted in a cupola or common fuel-fired furnace without flux, the sulphur content is increased. This increase is the result of an absorption of sulphur dioxide (SO_2) from the fuel. Moldenke[1]* gives the average increase of sulphur in the iron to be 0.02 per cent in good cupola practice and as high as 0.06 per cent in poor cupola practice. This percentage continues to increase during each remelting, resulting in a sulphur content of about 0.12 per cent for the best machinery iron scrap available at the present time.

3. Present day specifications for cast iron limit the sulphur content to 0.10 or 0.12 per cent. These limits require that the foundrymen use more expensive low-sulphur pig iron and less high-sulphur, low-cost scrap in their furnace charges to keep sulphur under the specified maximum limits.

4. Desulphurizing molten cast iron in the furnace, forehearth, or ladle has become accepted practice during the past 10 years as a means of keeping sulphur down to the specified limits. Evans[2] recommended 10 lb. of fused soda ash (commercial sodium carbonate) added to a ton of metal in the ladle to decrease the sulphur content 50 per cent. Girardet and Lelievre[3] also investigated the desulphurization of cast iron with sodium carbonate. Bettendorf and Wark[4] recommended lime (calcium oxide) and fluorspar (calcium fluoride) as the most efficient desulphurizers. Many other investigators have condemned sulphur in amounts over

* Superior numbers refer to bibliography at end of this paper.

0.10 per cent, as being harmful to the properties of cast iron and have devised methods of reducing it by chemical means.

5. A few investigators have denied that the presence of sulphur is a source of certain trouble. Moldenke[5] stated that it was possible to make soft and machinable castings containing 0.22 per cent sulphur with a normal silicon content. The American Society for Testing Materials[6] advanced the limit of sulphur to 0.17 per cent about 1924 in its standard specifications for chilled car wheels. They have decreased the permissible amount present until now 0.14 per cent is the limit. The specifications state that the minimum percentage of manganese shall not be less than three times the sulphur content.

6. Hurst[7] states that British foundrymen for some time have recognized that sulphur in cast iron is not necessarily harmful.

7. A careful survey of available literature, back to 1910, showed only one investigation where the influence of sulphur on the physical properties of cast iron had been tested under actual foundry practice. Smith and Riggan[8] concluded from two hundred series of tests on cupola cast iron that (1) the strength and fluidity of cast iron are not affected by sulphur; (2) Brinell hardness and combined carbon increase with sulphur content; (3) machinability decreases with an increase in sulphur content; (4) the sulphur content can be decreased by manganese additions and manganese is decreased by sulphur additions; and (5) sulphur up to 0.18 per cent has little effect on the properties of gray iron if the iron has a correct percentage of manganese.

SCOPE OF PRESENT INVESTIGATION

8. The research the authors are describing consisted in making and testing 40 casts of electric furnace cast iron in the form of various test bars. These bars were tested for transverse strength, deflection, tensile strength, flowability, machinability, hardness, contraction, depth of chill, chemical analysis and microstructure.

9. It would be impossible to investigate the effects of sulphur in all different compositions of electric furnace iron or in any one composition poured at all possible pouring temperatures. The composition, therefore, was kept as nearly constant as possible, varying only the amounts of sulphur. The objective was to work with

ordinary commercial metal and duplicate the usual pouring temperatures. The iron was heated to 2800°F. and poured at 2600°F.

Metals Used

10. Metals used for furnace charges consisted of two grades of pig iron, steel forge scrap, commercial stick iron sulphide, and granulated ferromanganese. The chemical analyses of these raw materials are shown in Table 1.

Table 1

CHEMICAL COMPOSITION OF RAW MATERIALS

	Carbon, Per Cent	*Silicon, Per Cent*	*Manganese, Per Cent*	*Sulphur Per Cent*	*Phosphorus, Per Cent*
Pig Iron *A*	3.97	2.96	1.12	0.013	0.13
Pig Iron *B*	3.19	2.85	0.90	0.028	0.13
Steel Scrap	0.20	0.03	0.52	0.028	0.022
Iron Sulphide				26-28	
Ferromanganese	5.00 (approx.)		80-85		

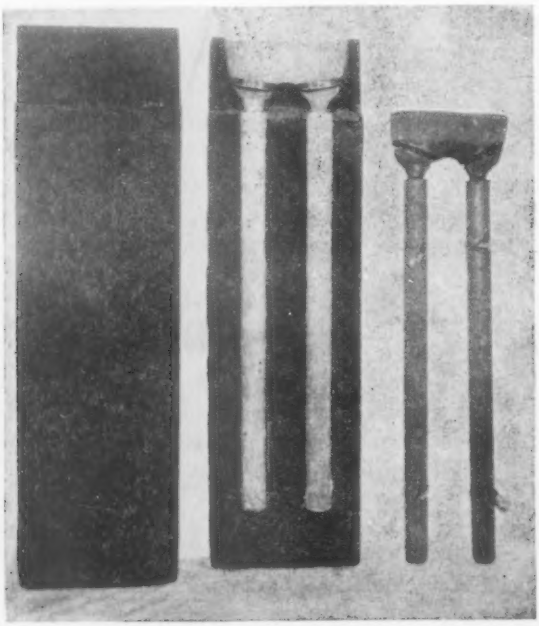


FIG. 1—VERTICAL TRANSVERSE TEST BAR MOLD.

FOUNDRY PROCEDURE

11. The foundry technique used in making test bar molds, and melting and pouring the metal, was developed especially for this investigation to maintain, as nearly as possible, constant conditions.

Preparation of Molds

12. Molds for transverse test bars and chill test bars were baked molds of core sand having the following composition by volume: 48 parts silica sand, 1 part linseed oil, and 2 parts water. When baked for 4 hr. at 425°F., the mixture showed a permeability of 85 to 95. The vertical transverse test bar mold, consisting of a double mold cavity, strainer cores, and pouring basin, is shown in Fig. 1.

13. Molds for the flowability, step and contraction test bars were made from green synthetic molding sand on a combination jolt-squeeze molding machine. The synthetic sand had the following composition by volume: 24 parts silica sand, ¾ parts bentonite, ¼ part cereal flour, and 1½ parts water. When squeezed at a pressure of 70 lb. per sq. in., the sand had a green permeability of 75 to 85 and a green compressive strength of 5 lb. per sq. in. The molding machines, pattern equipment, and finished molds ready for closing, are shown in Figs. 2 and 3.

Melting

14. An electric, rocking, indirect-arc furnace was lined with mullite bricks and, when found necessary, was patched with the same material.

15. The furnace was cleaned of all slag, patched, and started from room temperature for each heat. The lining was preheated to 1500°F. before the furnace was charged. The charge, consisting of 180 lb. of pig iron, 20 lb. of scrap steel and the iron sulphide additions, was placed in the hot furnace so that the sulphide sticks were protected from the arc by the pig iron and the steel scrap. The pouring spout of the furnace was partially closed with a brick and melting was started.

16. Heats, of two casts each, were made from a charge of pig iron *A*, steel scrap and iron sulphide. This metal was super-

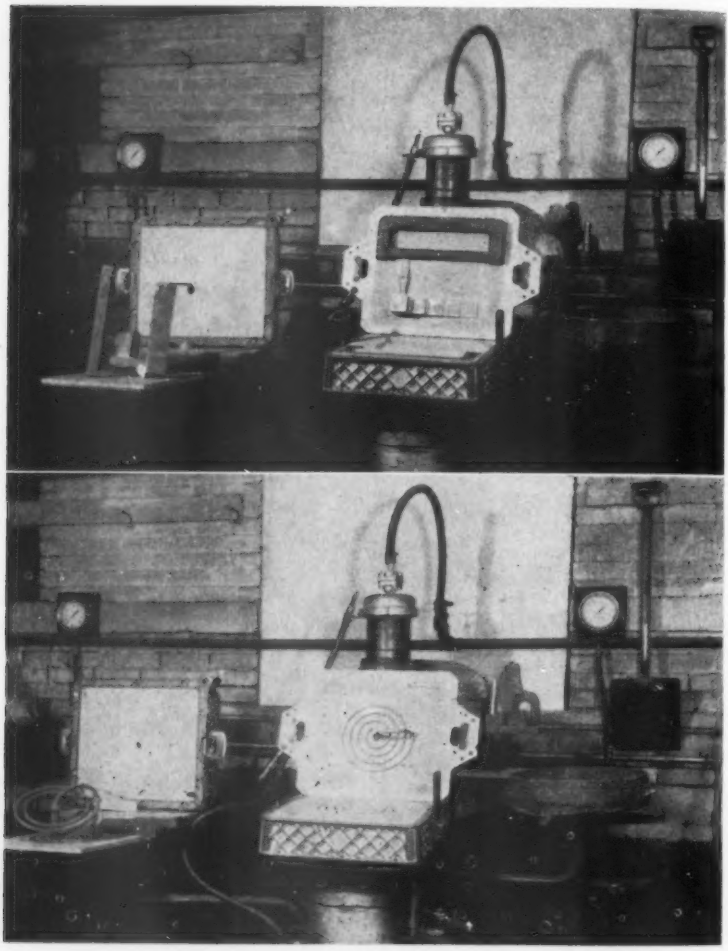


FIG. 2—TOP—COMBINATION JOLT-SQUEEZE MOLDING MACHINE SHOWING SYNTHETIC GREEN SAND STEP AND CONTRACTION TEST BAR MOLD READY FOR CLOSING. FIG. 3—BOTTOM—MOLDING MACHINE SHOWING SYNTHETIC GREEN SAND FLOWABILITY TEST BAR MOLD READY FOR CLOSING.

heated to 2800°F. and half of it was poured at 2600°F. into the test bar molds. This portion of the heat was designated as the first cast of the heat and the test bars poured from it were given even numbers. The second portion, or cast, from each heat was poured at 2600°F. from the same metal after a ferromanganese addition had been made, and the metal heated to 2800°F. The test bars made from the second cast of each heat were given odd

numbers, one higher in number than the first cast of the heat. The cast numbers of these heats are 10 through 29 and are called series *A*.

17. The furnace input for this series of heats was 90 k.w. per hr. requiring a total of 92 k.w. hr. to heat the metal to 2800°F. for the first cast. Melting time averaged 1 hr. and 8 min. The second cast required 10 k.w. hr. additional input.

18. Ten heats of two casts each were made from a charge of pig iron *B*, steel scrap and iron sulphide, using a faster melting rate. These heats were duplicates of series *A*, except for melting time. The cast numbers of these heats are 30 through 49 and are called series *B*.

19. The main difference between series *A* and *B* was that series *A* casts had a higher initial content of manganese and a melting time of 12 min. longer than series *B*.

20. The furnace input for this series of heats was 110 k.w. per hr. requiring 88 k.w. hr. to bring the metal up to 2800°F. for the first cast. The melting time averaged 55 min. The second cast required 8 k.w. hr. additional input.

21. Rocking cycle of the furnace during melting was 2 notches at 40 k.w. input, 4 notches at 50 k.w. input and 8 notches at 60 k.w. input. The furnace was shut off after 92 k.w. input for series *A*, and 88 k.w. input for series *B* and the temperature of the metal measured.

22. If the superheat temperature was not up to 2800°F., melting was continued until this temperature was reached. Several heats were over-heated and the excess superheat temperature was plus or minus 20°F. Table 2 shows how records of furnace heats are kept at the University of Minnesota.

Temperature Measurements

23. Superheat and pouring temperatures of the metal were measured with a calibrated tungsten-graphite thermocouple. This thermocouple was developed and built after serious difficulties were encountered in trying to use a platinum-platinum-10-per-cent-rhodium couple and an optical pyrometer. Nine preliminary casts were discarded because of errors in optical pyrometer readings caused by smoke and fumes, and because of failures in obtaining a

fast, accurate temperature reading with the platinum-platinum-10-per-cent-rhodium couple.

Table 2

UNIVERSITY OF MINNESOTA

Mechanical Engineering Department
Foundry Laboratory

FURNACE HEAT 46

DATE _____ ROOM TEMPERATURE _____ °C. 75 °F.

CHARGE	C	Si	S	Mn	P	Weight
1. Pig Iron	3.91%	2.85%	0.028%	0.90%	0.13%	180 lbs.
2. Iron Scrap	%	%	%	%	%	lbs.
3. Steel Scrap	0.20%	0.03%	0.028%	0.52%	0.022%	20 lbs.
4. Total Metals Charged						200

ADDITIONS		
5. Carburizer		lbs.
6. Ferro-silicon	% Si	lbs.
7. Ferrous sulphide	26-28% S	¼ lbs.
8. Ferro-manganese	% Mn	lbs.
9. Ferro-phosphorus	% P	lbs.

MELTING			
10. Charge number	1	2	3
11. Arc off	:	:	2:32
12. Arc on	1:38	:	:
13. Total time			54
14. Rocking started	2:05	2:11	2:17
15. Number of notches	2	4	9
16. KW input			88
17. KW input per minute			1.64
18. Ratio of KW/lb. of metal melted			
19. Pounds of metal melted/minute			

FURNACE TEMPERATURE

20. Thermocouple 111 Millivolts 36.4 _____ °C. 2800°F.

POURING TEMPERATURE

21. Thermocouple _____ Millivolts 34.6 _____ °C. 2600°F.

POUNDS OF METAL USED			
22. Ladle No. 1	61 lbs. —	40 lbs. =	21 lbs.
23. Ladle No. 2	63 lbs. —	43 lbs. =	20 lbs.
24. Ladle No. 3	63 lbs. —	41 lbs. =	22 lbs.
25. Ladle No. 4	60 lbs. —	35 lbs. =	25 lbs.
26. Ladle No. 5	52 lbs. —	37 lbs. =	15 lbs.
27. Ladle No. 6	lbs. —	lbs. =	lbs.
28.		TOTAL	103 lbs.

NOTES: Slightly wild in furnace and ladle
Very small amount of slag
Appears hot, white color to metal
Appears fluid.

Test run by: _____ H. /38

24. The tungsten-graphite couple was checked for errors in calibration after every 40 immersions or 4 casts. The construction and method of calibration is shown in a paper by one of the authors.[9]

Pouring

25. Molten iron was poured from the furnace into a small 25-lb. preheated hand ladle. The tungsten-graphite thermocouple was immersed in the metal while the ladle and metal were being weighed. The metal was slowly stirred with the thermocouple to obtain a uniform temperature in the metal. When the iron reached a temperature of 2600°F., it was poured into a test bar mold. The ladle was reweighed after pouring to determine the weight of the metal removed from the furnace. The hand ladle was refilled and the procedure repeated. The order of pouring the test bar molds was: (1) Transverse test bars *a* and *b*, (2) flowability test bar and chill test bar, (3) step test bar and contraction test bar and (4) transverse test bars *c* and *d*. The furnace, test bar molds and scales are shown in Fig. 4.

26. The weight of the metal removed from the furnace was determined and the remaining metal was poured into pigs until only 100 lb. remained in the furnace.

FIG. 4—FURNACE, TEST BAR MOLDS AND SCALES.

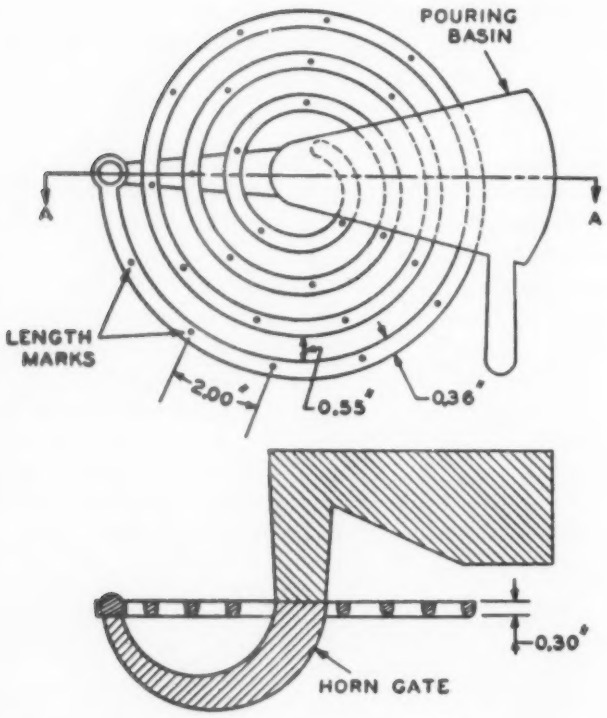


FIG. 5—FLOWABILITY TEST SPECIMEN

27. The second part, or cast, of the heat consisted of making an addition of ferromanganese to the remaining molten metal and reheating to 2800°F. This required an additional 10 k.w. input, taking 8 min. time. The metal was poured in the same manner and at the same temperature as the first 100 lb. cast.

28. The test bars were left in their molds until they had reached room temperature. The bars then were removed from the molds and labelled with zinc tags, wired to the casting.

DETERMINATION OF PROPERTIES

29. Test bar castings were tested for transverse strength, tensile strength, flowability, depth of chill, contraction and machinability.

Transverse Test

30. Four transverse test bars, 21-in. long and of 1.20-in. diameter, were made from each cast. These bars were broken on 18-in. supports with a hand-operated transverse machine. Deflection of the specimen was read at 1500-lb. load and at the breaking load. The diameter of the bar at the break was measured and if found to be other than 1.20-in., a correction factor[10] was applied to the breaking load.

Tensile Test

31. A tensile test bar was machined from the lower half of three transverse test bars from each cast. The standard A.S.T.M. dimensions[10] were used with a polished neck diameter of 0.800-in. The tensile bars were tested in a 50,000-lb. capacity tensile machine using a pulling speed of 0.05 in. per min.

Flowability Test

32. The flowability test bar[11] (Fig. 5) was measured when removed from the mold. The 2-in. reference marks along the upper surface of the bar were counted and the number of inches the metal had run in the mold was recorded.

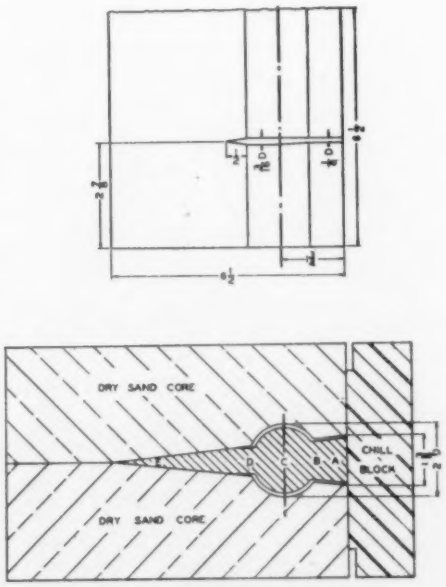


FIG. 6—CHILL TEST SPECIMEN

Chill Test

33. The chill test bar (Fig. 6) was broken in the center while held in a special cast iron breaking block. The depth of chill at points *A* and *E* was measured and the appearance of the fracture at points *B*, *C* and *D* was recorded.

Contraction Test

34. The gage bar (Fig. 7) was part of the mold. The molten metal, upon solidifying, took the shape of the mold cavity which was 1-in. square by 12-in. long. The difference in length of the bar at room temperature and at freezing temperature was measured and recorded in 64ths of an inch contraction per foot length.

Machinability Test

35. Machinability was determined by measuring the time required for a drill, driven at a constant speed under a constant load, to penetrate the metal a definite depth.

36. The size and shape of the step test bar used for the machinability test is shown in Fig. 8. This bar was held in a vise on the table of a 14-in. drill press as shown in Fig. 9.

37. The $\frac{3}{8}$-in. high-speed drill was driven at 474 r.p.m. by the V-belt drive. A constant 160-lb. load was applied to the drill by means of a weight hung on a $\frac{1}{8}$-in. steel tiller rope which passed over and was attached to a sheave pulley. The casting was spot drilled at *A*, *B*, *C*, *D* and *E*, Fig. 8, with a used drill to remove any sand or scale. Holes were then drilled at these points using a freshly-sharpened drill for each hole. Time readings were taken with a stop watch for each $\frac{1}{4}$-in. of penetration in the 2-in. and 1-in. sections, for each $\frac{1}{8}$-in. of penetration in the $\frac{1}{2}$-in. section,

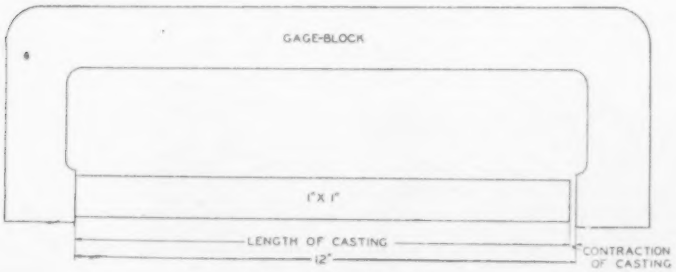


FIG. 7—CONTRACTION TEST SPECIMEN

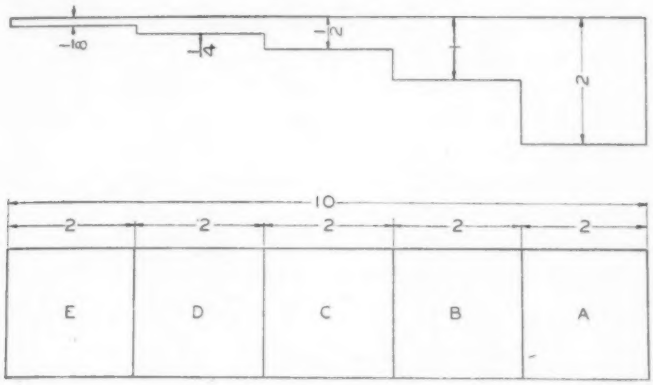


FIG. 8—STEP TEST SPECIMEN

and for each ⅛-in. of penetration in the ¼-in. section. The ⅛-in. section was tested only as machinable or not machinable. The depth of penetration was measured on the graduated spindle of the drill press. A second run was made on the 2-in. and 1-in. sections, using the same respective drill to check on the wearing of the cutting edge. A typical result sheet for a test is shown in Table 3. Each hole, except in the duplicate runs, was made with a drill sharpened in a precision drill grinding machine.

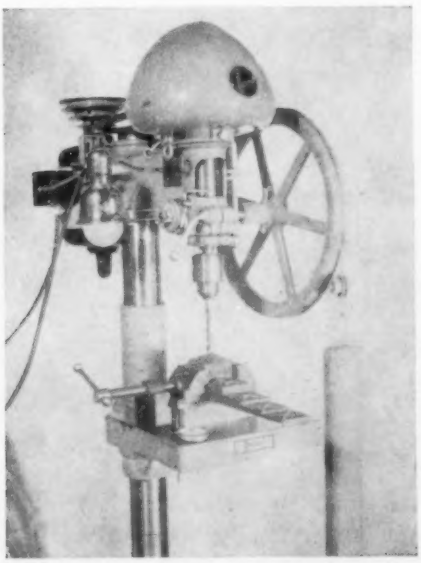


FIG. 9—APPARATUS USED FOR MACHINABILITY TEST

Table 3

TYPICAL MACHINABILITY DATA SHEET

Test Bar No. 22 Series *A*

Readings = Time in hundredth of minutes

Depth of Drill Penetration in inches	*2 inch*		*1 inch*		*½ inch*	*¼ inch*	*⅛ inch*
1 7/8	76	83					
1 3/4	70	77					
1 1/2	60	64					
1 1/4	50	53					
1	40	42					
7/8			36	34			Machinable
3/4	31	33	30	30			
5/8							
1/2	21	22	20	20			
3/8					14		
1/4	10	12	11	11	10	7	
3/16							
1/8	4	5	5	6	5	5	
1/16						3	
0							
	1st run	Re-run	1st run	Re-run			
Machinability Number	10		10		10	10	

38. The machinability number used in this investigation is equal to the number of hundredths of a minute required to drill 3/8-in. diameter hole 1/4-in. in depth at 474 r.p.m. under 160-lb. vertical load. The decrease in number represents an increase in machinability.

Chemical Analysis

39. The determinations of the chemical analyses were made by the standard methods; however sulphur was determined gravimetrically.

RECORDING OF RESULTS

40. Physical properties, obtained from the test specimens, were entered on individual report sheets and the resulting properties calculated. A typical report sheet of the machinability tests is shown in Table 4. A typical report sheet of the physical properties tests is shown in Table 6. Only one of these sheets is included in this report. The chemical analyses for the casts of series *A* are shown in Table 5, and those of series *B* in Table 7. The properties obtained from the report sheets are plotted curve sheets, Figs. 10 through 17.

Table 4

TYPICAL RESULT SHEET FROM MACHINABILITY TESTS

Series *B* First Cast

Average time in hundredths of a min. to drill 3/8-in. hole 1/4-in. deep at 474 r.p.m. under 160-lb. load.

Cast No.	*Sulphur, per cent*	*Section Size* 2 *in.*	1 *in.*	½ *in.*	¼ *in.*	⅛ *in.**
38	0.027	11	13	13	12	s.
30	0.097	14	13	14	14	m.
46	0.110	14	14	14	16	u.
44	0.14	12	12	14	14	m.
32	0.172	11	11	11	12	m.
48	0.207	12	14	16	14	m.
34	0.281	13	13	14	14	m.
36	0.295	15	16	16	16	m.
42	0.36	18	20	23	23	m.
40	0.500	25	26	25	28	s.

*m. denotes machinable for ⅛ in. section.
u. denotes unmachinable for ⅛ in. section.
s. denotes slightly machinable for ⅛ in. section.

DISCUSSION OF RESULTS

41. The test results of the *B* series show more uniformity than the *A* series. This was due to the faster melting rate used in the *B* series and the experience and data obtained from the *A* series which was used in planning the later casts.

42. The chemical analyses of the casts from the first part of each heat showed a definite drop in manganese content as the sulphur content was increased. This decrease in manganese was more rapid as the sulphur content was increased beyond 0.18 per cent.

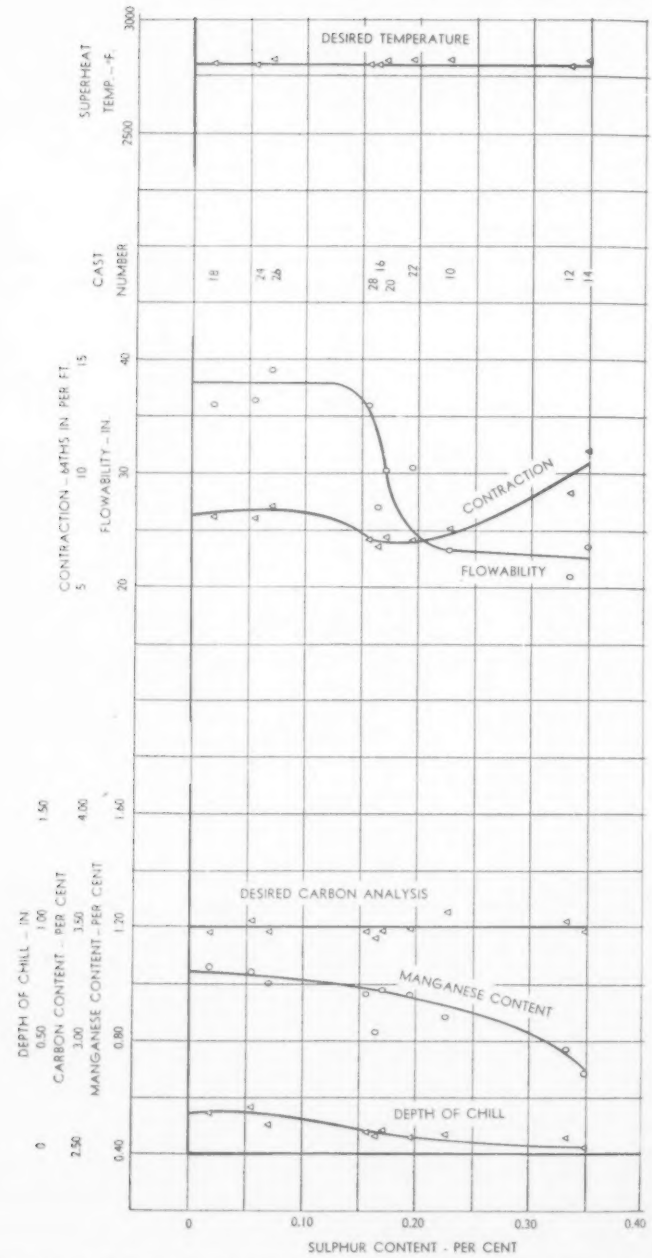


FIG. 10—EFFECT OF SULPHUR ON PROPERTIES OF ELECTRIC FURNACE CAST IRON. FIRST CASTINGS FROM SERIES *A* HEATS. POURING TEMPERATURE 2600°F.

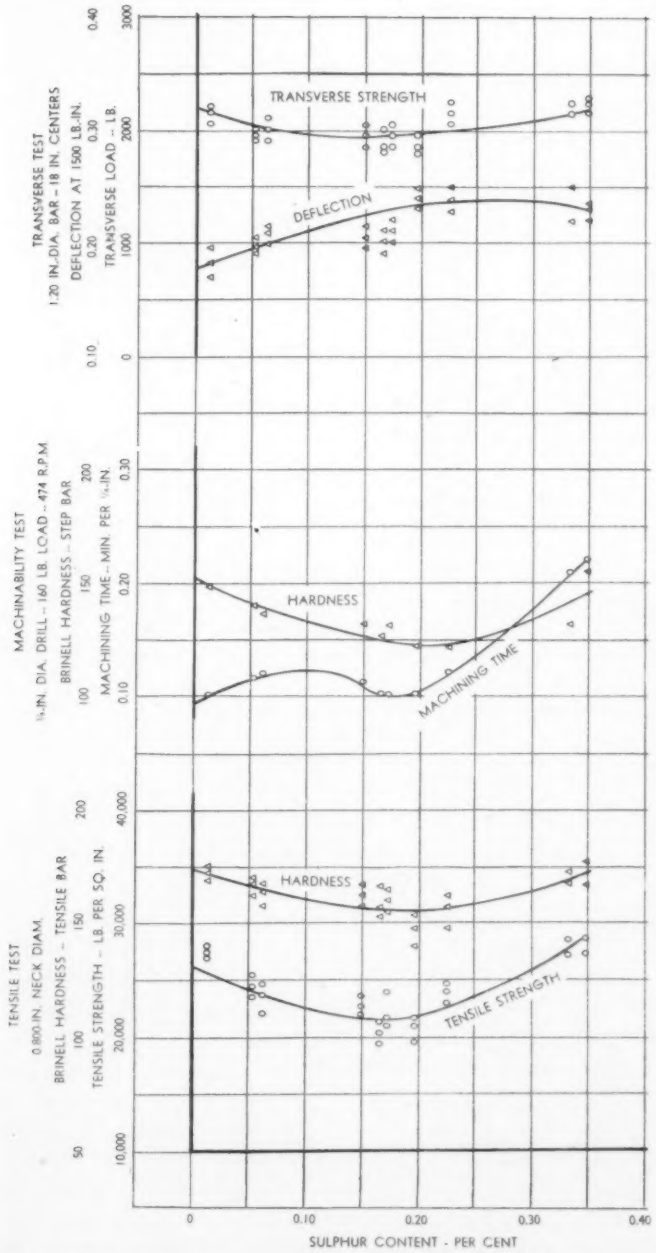
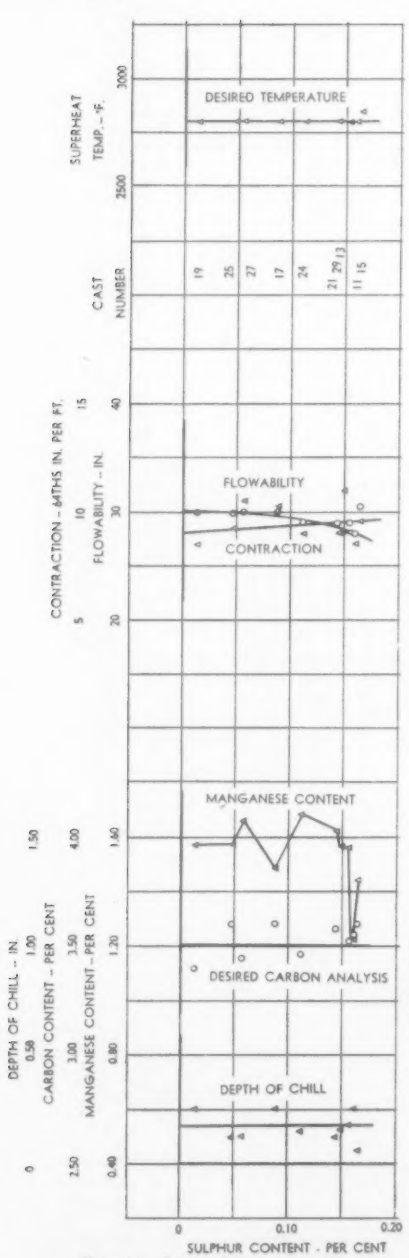


FIG. 11—EFFECT OF SULPHUR ON PROPERTIES OF ELECTRIC FURNACE CAST IRON. FIRST CASTS FROM SERIES *A* HEATS. POURING TEMPERATURE 2600°F.



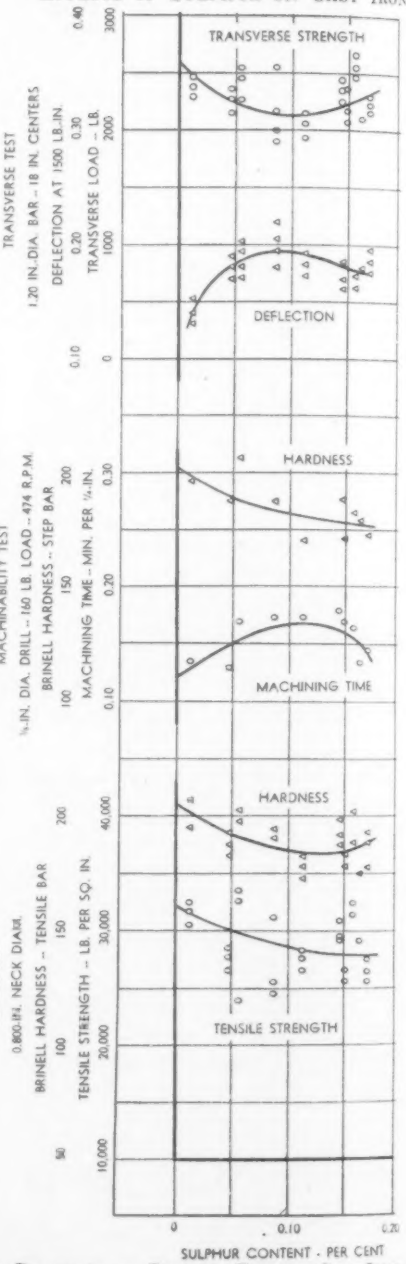

TRANSVERSE TEST
1.20 IN. DIA. BAR - 18 IN. CENTERS
DEFLECTION AT 1500 LB. IN.
TRANSVERSE LOAD - LB.
TRANSVERSE STRENGTH
DEFLECTION
MACHINABILITY TEST
½ IN. DIA. DRILL - 160 LB. LOAD - 474 R.P.M.
BRINELL HARDNESS - STEP BAR
MACHINING TIME - MIN. PER ½ IN.
HARDNESS
MACHINING TIME
TENSILE TEST
0.800 IN. NECK DIAM.
BRINELL HARDNESS - TENSILE BAR
TENSILE STRENGTH - LB. PER SQ. IN.
HARDNESS
TENSILE STRENGTH
SULPHUR CONTENT - PER CENT

FIG. 12—LEFT—EFFECT OF SULPHUR ON PROPERTIES OF ELECTRIC FURNACE CAST IRON. SECOND CASTS FROM SERIES *A* HEATS. POURING TEMPERATURE 2600°F. FIG. 13—RIGHT—EFFECT OF SULPHUR ON PROPERTIES OF ELECTRIC FURNACE CAST IRON. SECOND CASTS FROM SERIES *A* HEATS. POURING TEMPERATURE 2600°F.

Table 5

CHEMICAL ANALYSIS, PER CENT BY WEIGHT

Series *A*

Cast Number	*C*	*Si*	*Mn*	*S*	*P*
10	3.56	2.49	0.86	0.228	0.13
11	3.56	2.46	1.23	0.161	0.12
12	3.53	2.45	0.77	0.331	0.13
13	3.54	2.40	1.56	0.152	0.13
14	3.48	2.52	0.67	0.349	0.13
15	3.40	2.57	1.45	0.163	0.13
16	3.45	2.65	0.83	0.165	0.13
17	3.51	2.61	1.48	0.086	0.14
18	3.46	2.58	1.06	0.017	0.13
19	3.41	2.64	1.57	0.014	0.13
20	3.48	2.61	0.98	0.171	0.13
21	3.53	2.56	1.63	0.144	0.12
22	3.49	2.44	0.96	0.198	0.13
23	3.48	2.55	1.69	0.111	0.11
24	3.54	2.51	1.04	0.057	0.12
25	3.52	2.57	1.58	0.047	0.15
26	3.49	2.50	1.00	0.068	0.11
27	3.45	2.54	1.68	0.056	0.12
28	3.49	2.53	0.98	0.153	0.12
29	3.42	2.57	1.56	0.147	0.12

43. Manganese in cast iron is present as an oxide, as iron-manganese carbide ($[FeMn]_3C$), and as manganese sulphide (MnS), or manganese sulphide-iron sulphide (MnS · FeS). With the large amount of silicon and carbon present, it is doubtful whether much of the manganese was lost by oxidation. The manganese, which forms manganese carbide by combination with carbon, is not lost and is part of the reported manganese. The manganese which combines with sulphur forms manganese sulphide from the reaction $Mn + S = MnS$ requiring 1.73 parts by weight of manganese and 1 part by weight of sulphur to form 2.73 parts by weight of manganese sulphide. If the sulphur is present as iron sulphide, the manganese forms manganese sulphide from the reaction $FeS + Mn = MnS + Fe$ which, according to Herty and True[12] is reversible.

44. This manganese sulphide, according to Rohl[13], has a melting point of about 2950°F. and hence is a solid at the temperatures used in this investigation. Moldenke[5] reports the specific gravity of manganese sulphide to be about 3.55 as compared to

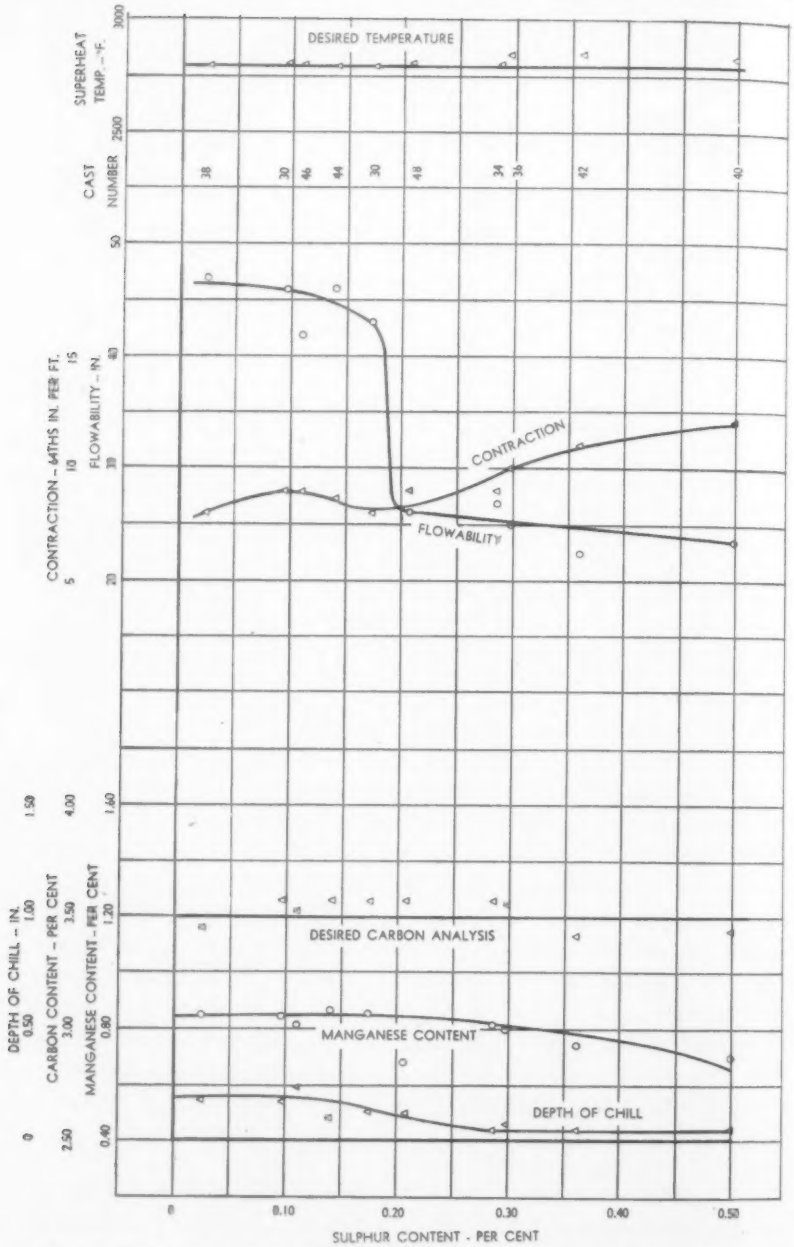


FIG. 14—EFFECT OF SULPHUR ON PROPERTIES OF ELECTRIC FURNACE CAST IRON. FIRST CASTS FROM SERIES *B* HEATS. POURING TEMPERATURE 2600°F.

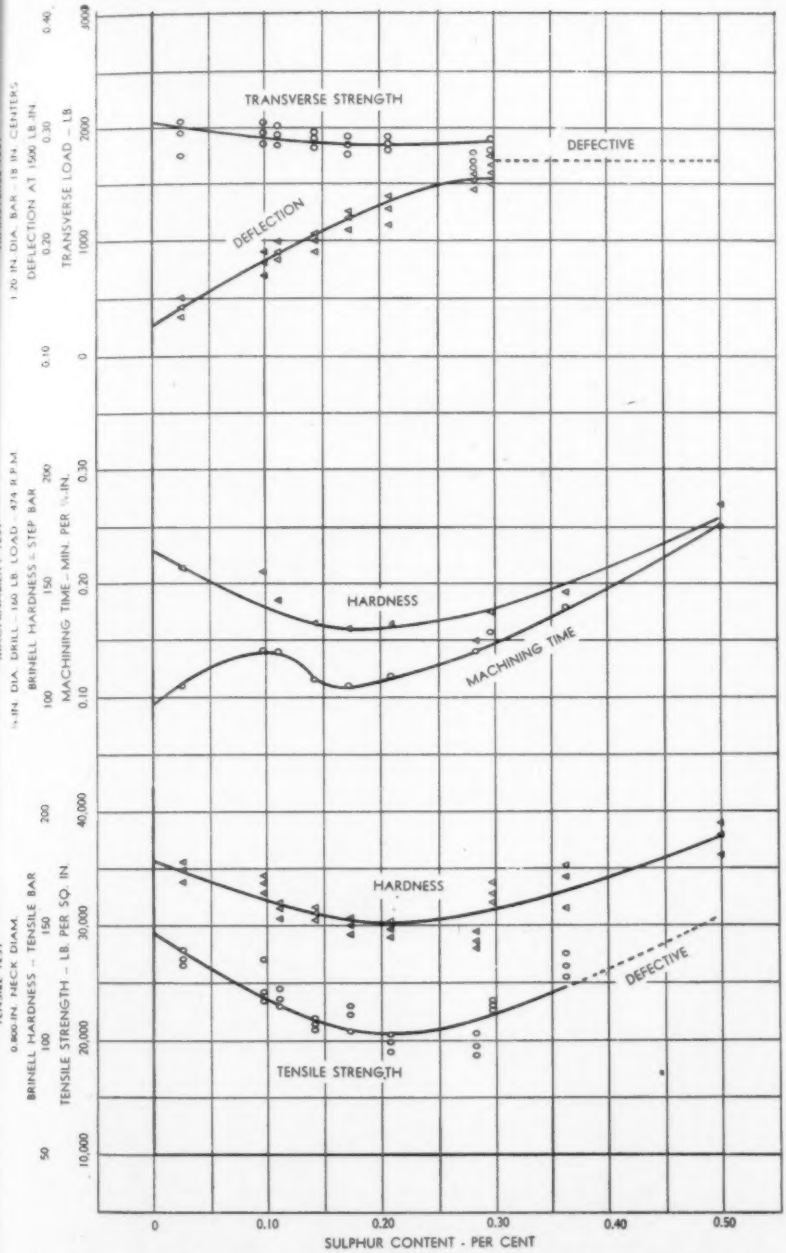


FIG. 15—EFFECT OF SULPHUR ON PROPERTIES OF ELECTRIC FURNACE CAST IRON. FIRST CASTS FROM SERIES *B* HEATS. POURING TEMPERATURE 2600°F.

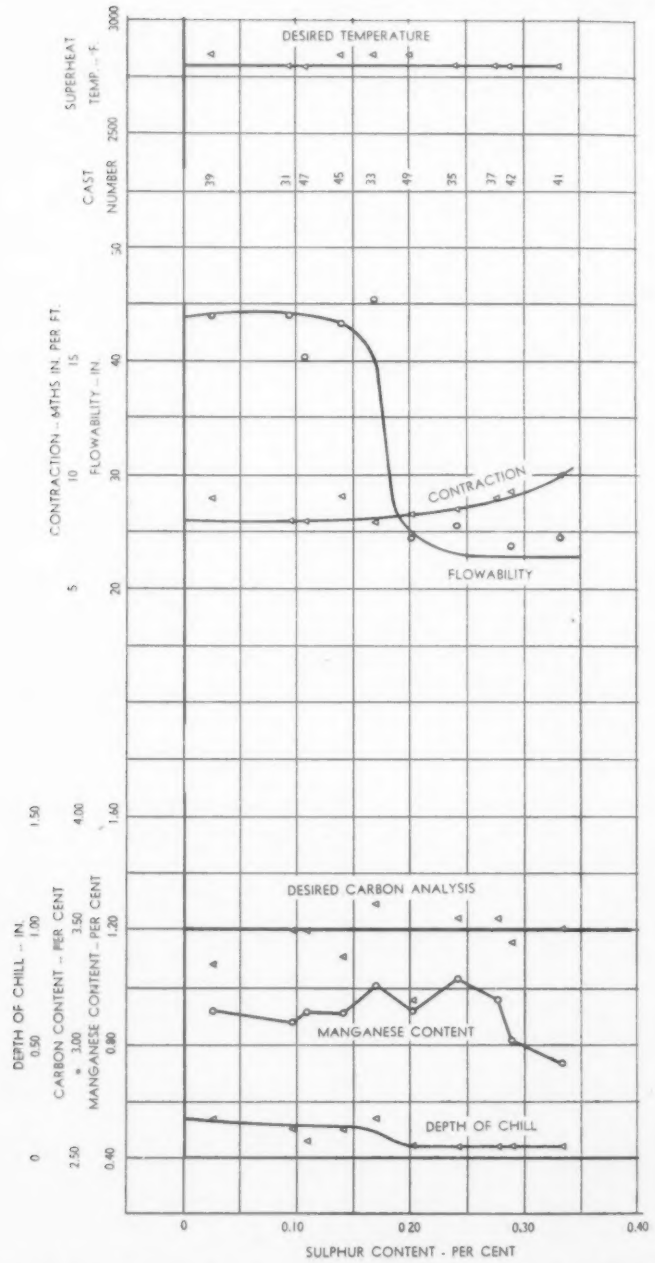


FIG. 16—EFFECT OF SULPHUR ON PROPERTIES OF ELECTRIC FURNACE CAST IRON. SECOND CASTS FROM SERIES H HEATS. POURING TEMPERATURE 2600°F.

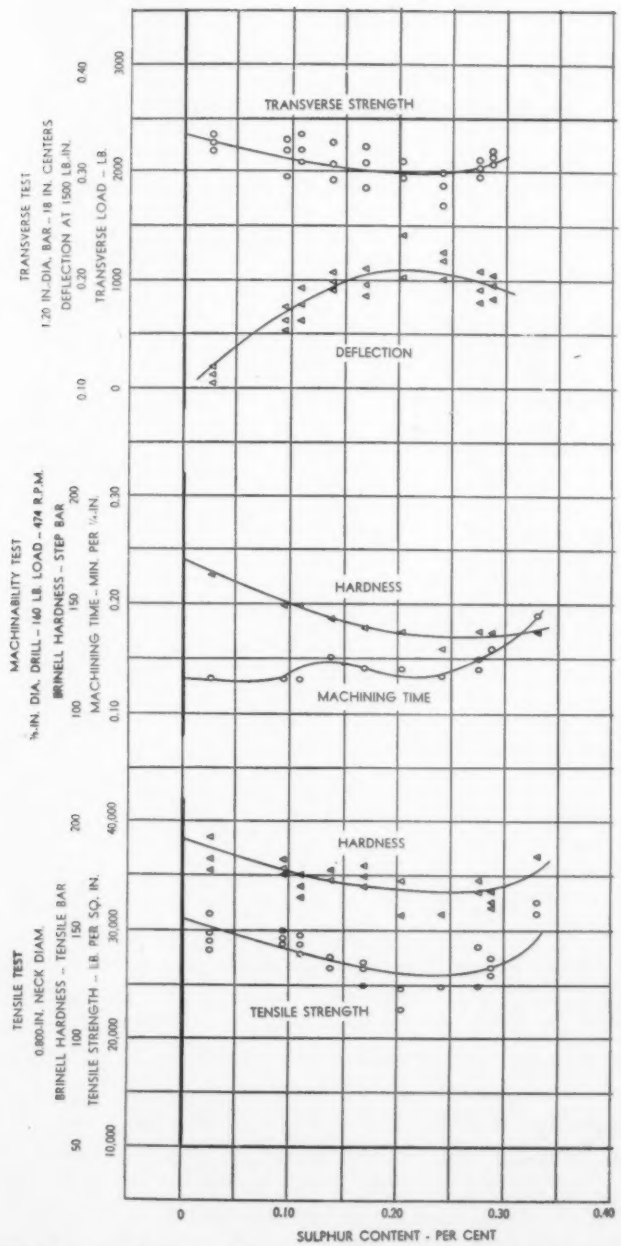


FIG. 17—EFFECT OF SULPHUR ON PROPERTIES OF ELECTRIC FURNACE CAST IRON. SECOND CASTS FROM SERIES *B* HEATS. POURING TEMPERATURE 2600°F.

Table 6

UNIVERSITY OF MINNESOTA

Mechanical Engineering Department
Foundry Laboratory

HEAT NUMBER 26 SERIES A-3 DATE

1. TRANSVERSE TEST:

Bar No.	Pounds Load	Diam.	Corrected Load	Def. per 1500 lbs.	Def. per break
A	2100	1.20	2100	.19	.29
B	2000	1.20	2000	.19	.28
C	2080	1.21	2026	.22	.35
D	1860	1.20	1860	.20	.29

2. TENSILE TEST:

Bar No.	Pounds Load	Area	Pounds per Square inch	Brinell Hardness
A	12270	½	24540	4.70 = 163
B	12230	½	24460	4.65 = 166
C				
D	10650	½	21300	4.80 = 156

3. FLOWABILITY TEST:

Flow in notches 19½ x 2 39 inches

4. CONTRACTION TEST:

Gage length = 12.000 inches
Gage—test bar = inches
Contraction/ft. = 8/64 inches

5. STEP-BAR TEST:

	Chill	B. Hardness	Mach.—Min./¼" unmachinable
⅛ in. section			
¼ in. section			.13
½ in. section			.13
1 in. section			.13
2 in. section			.12

6. CHILL AND SHRINK TEST:

Depth of "A" chill ⅛ inches
Depth of "E" chill inches
Porosity at "C"
Brinell Hardness A
B
C
D
E

7. CHEMICAL ANALYSES:

C%	Si%	Mn%	S%	Ph%	
3.49	2.50	1.00	.068	.11	

Test Run By: FH 39

Table 7

CHEMICAL ANALYSIS, PER CENT BY WEIGHT

Series *B*

Cast Number	*C*	*Si*	*Mn*	*S*	*P*
30	3.56	2.77	0.85	0.097	0.12
31	3.51	2.73	0.89	0.095	0.11
32	3.55	2.62	0.85	0.172	0.12
33	3.53	2.64	1.01	0.170	0.12
34	3.57	2.61	0.81	0.281	0.13
35	3.55	2.68	1.09	0.241	0.13
36	3.55	2.68	0.80	0.295	0.11
37	3.52	2.67	0.97	0.277	0.12
38	3.45	2.65	0.85	0.027	0.12
39	3.37	2.70	0.91	0.028	0.13
40	3.44	2.68	0.70	0.500	0.11
41	3.52	2.72	0.74	0.332	0.11
42	3.41	2.67	0.73	0.360	0.11
43	3.46	2.70	0.81	0.289	0.12
44	3.57	2.68	0.87	0.140	0.12
45	3.42	2.69	0.92	0.139	0.12
46	3.51	2.66	0.82	0.110	0.12
47	3.52	2.65	0.90	0.109	0.12
48	3.57	2.61	0.66	0.207	0.12
49	3.47	2.63	0.94	0.203	0.12

7.20 for molten iron. As this solid manganese sulphide, having only half the specific gravity of iron, is formed, it will tend to float to the surface of the metal and be skimmed off as slag. This decrease in manganese content with an increase in sulphur content agrees with the results reported by Smith and Riggan[8].

45. The chemical analyses of the casts from the second part of each heat showed a definite drop in sulphur content as the manganese increased. This decrease in sulphur content was proportionally greater in the heats that were superheated above 2800°F. and in the heats where the melting time was long. These results prove that manganese is a desulphurizer in electric furnace cast iron. This desulphurizing action of manganese limited the amount of sulphur which remained in the second part of each heat. The second cast of the heats in series *B* were heated more rapidly and for a shorter length of time than those in series *A* and had a lower manganese content. Hence, a sulphur content of 0.332 per cent was retained in series *B* as compared to 0.163 per cent retained in series *A*. This does not agree with the results ob-

tained by Shaw[14], who believes manganese cannot lower the sulphur content under actual foundry conditions.

Effect of Sulphur on Molten Metal

46. Certain changes in the properties of the molten metal were noticed when the sulphur content was increased. The casts containing over 0.18 per cent sulphur had some slag on the metal when it was poured from the furnace, while casts below 0.18 per cent sulphur, except casts 16 and 48, were nearly free from slag. Upon holding in the ladle, slag formed rapidly in the casts high in sulphur where the manganese showed a decrease. This further indicates desulphurizing by the manganese.

47. The ladles, after pouring the high sulphur iron, were coated with a layer of slag which, upon further cooling, became liquid and ran as small drops to the bottom of the ladle. The metal and slag also adhered to the thermocouple and after the couple was removed started to become fluid and dripped off. This dripping would continue until the temperature of the couple dropped to 2120°F. and then the material would solidify. This happened in every case that the flowability test bar indicated poor flowability.

48. The molten metal containing high sulphur appeared sluggish and had a yellow orange color at 2600°F. compared to a white yellow color of the molten metal low in sulphur.

49. The molten metal occasionally seemed wild and would boil in the hot ladle or around the thermocouple, giving off a blue flame characteristic of carbon monoxide. The metal low in sulphur would boil and then become quiet in a few seconds after being in the ladle. The metal high in sulphur did not boil rapidly, but would continue boiling for a longer period of time.

Flowability

50. The flowability of the electric furnace cast iron decreased slightly with increase in sulphur content up to about 0.18 per cent. At this point, the flowability dropped sharply to about half its original amount. This dropping point is the same for both series and was not altered by manganese additions. The second casts of series *A* did not show this drop in flowability as the highest sulphur content was only 0.163 per cent.

51. Cross checking the flowability data also shows that the flowability decreases with an increase in manganese content for all casts having a sulphur content below 0.18 per cent and that the flowability has a tendency to increase with an increase in manganese content above 0.18 per cent. This change in flowability at 0.18 per cent sulphur content is caused by some of the solid manganese sulphide which did not have time to float to the slag making a sluggish mixture of a solid and a liquid. The rapid drop in flowability occurs at the same sulphur content where the manganese content started to decrease rapidly.

52. Comparisons of the flowability properties and the manganese contents show that a cast, having a manganese content either higher or lower than the average, will have a correspondingly higher or lower flowability number. Since all casts in each series started with the same manganese content, a lower value than the average indicates excess manganese sulphide in the metal. The flowability was less for the *A* series as the melting time was longer and the manganese content higher.

Inclusions

53. Inclusions, believed to be manganese sulphide or manganese sulphide-iron sulphide, were found in all microscopic specimens having a sulphur content over 0.10 per cent. The appearance of these inclusions are shown in Figs. 18, 19, 20 and 21. These photomicrographs were taken 10 mm. in from the surface of the middle section of a transverse test bar.

54. Fig. 18 shows a typical structure of a low sulphur electric furnace cast iron. It shows white ferrite grains surrounded by thin graphite flakes. The white dotted lakes are iron phosphide or steadite.

55. Fig. 19 shows a typical structure of an electric furnace cast iron of about 0.10 per cent sulphur. The gray inclusions are manganese sulphide. The graphite flakes are thin and seem to center around the manganese sulphide inclusions. Steadite is present as shown by the white dotted lakes.

56. Fig. 20 shows a typical structure of an electric furnace cast iron of about 0.18 per cent sulphur. The gray inclusions are probably a manganese-sulphide-iron-sulphide eutectic compound.

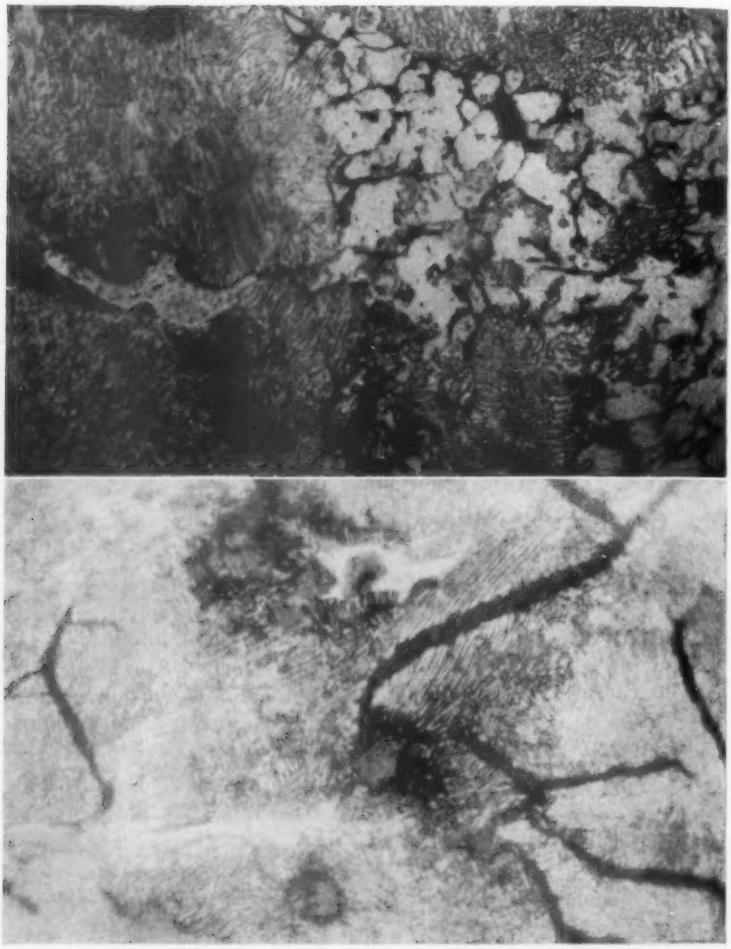


FIG. 18—TOP—ELECTRIC FURNACE CAST IRON, ETCHED WITH PICRIC ACID, X 1000. CAST NO. 38. SULPHUR 0.027 PER CENT, MANGANESE, 0.85 PER CENT. FIG. 19—BOTTOM—ELECTRIC FURNACE CAST IRON, ETCHED WITH PICRIC ACID, X 1000. CAST NO. 30. SULPHUR, 0.097 PER CENT, MANGANESE, 0.85 PER CENT.

The flakes of graphite are larger and more numerous than in Fig. 19. The pearlite laminations are spheroidal in appearance.

57. Fig. 21 shows a typical structure of an electric furnace cast iron of about 0.30 per cent sulphur. The graphite flakes are small and in some cases are of a whorl or rosette form. The manganese sulphide inclusions are large and numerous, some being speckled in appearance. The amount of manganese sulphide in

the specimens having a sulphur content above 0.18 per cent seemed to increase as the sulphur content increased. Microscopic specimens also showed more manganese sulphide in the top sections of the vertical cast transverse test bars than in the middle sections.

Contraction

58. The contraction of the cast iron, when it cooled from the freezing temperature to room temperature, increased with an

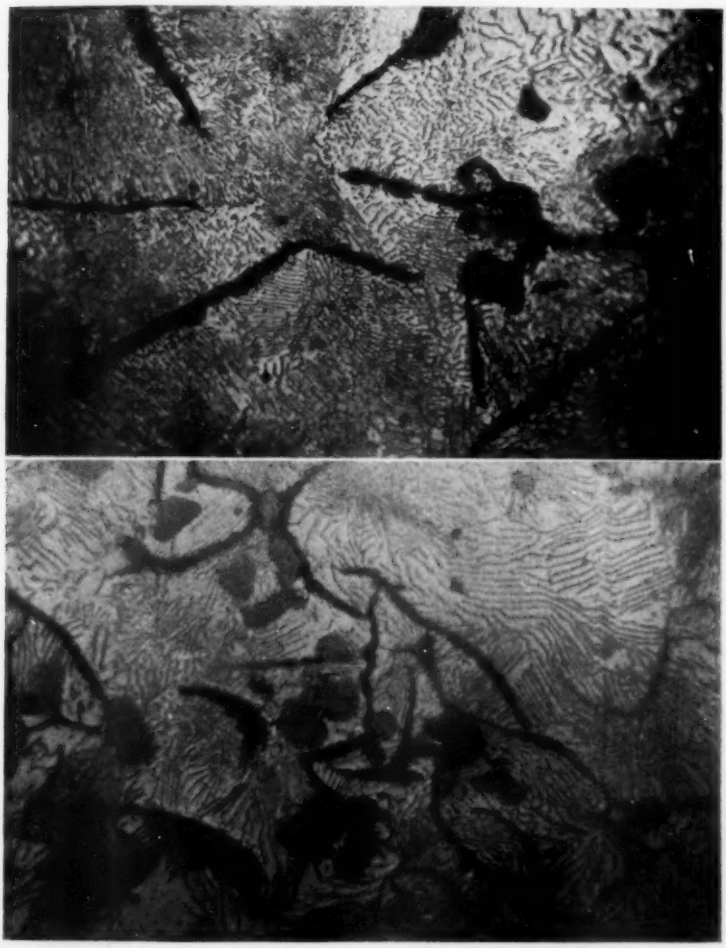


FIG. 20—TOP—ELECTRIC FURNACE CAST IRON ETCHED WITH PICRIC ACID, X 1000. CAST NO. 22. SULPHUR, 0.172 PER CENT, MANGANESE, 0.85 PER CENT. FIG. 21—BOTTOM—ELECTRIC FURNACE CAST IRON ETCHED WITH PICRIC ACID, X 1000. CAST NO. 36. SULPHUR, 0.295 PER CENT, MANGANESE, 0.80 PER CENT.

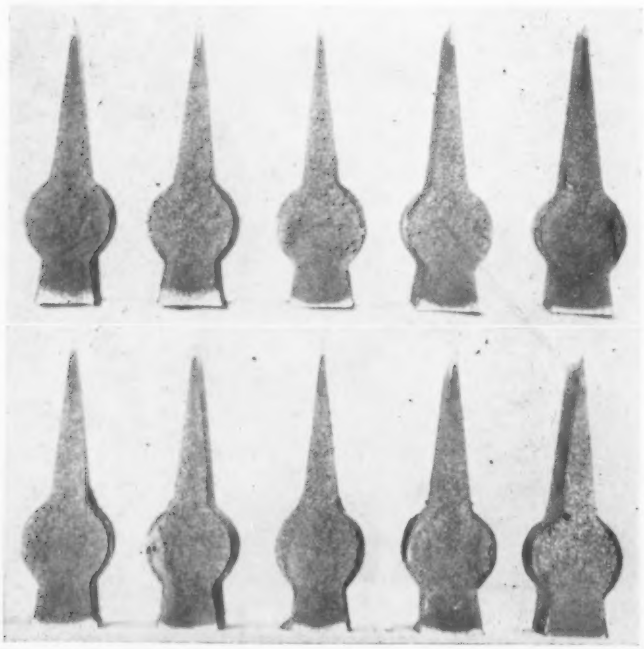


FIG. 22—FRACTURE OF CHILL TEST BARS — SERIES A — FIRST CASTS

TOP					
Cast Number	18	24	26	28	16
Sulphur, Per Cent.....	0.017	0.057	0.068	0.153	0.165
Manganese, Per Cent.....	1.06	1.04	1.00	0.98	0.834
BOTTOM					
Cast Number	20	22	10	12	14
Sulphur, Per Cent.....	0.171	0.198	0.228	0.331	0.349
Manganese, Per Cent.....	0.98	0.960	0.86	0.774	0.674

increase in sulphur content up to 0.10 per cent sulphur and then decreased as the sulphur increased to 0.18 per cent. A further increase in sulphur caused an increase in contraction. The broken tensile and transverse bars showed a large amount of graphite flakes at 0.027 per cent sulphur, a mottled fracture at 0.18 per cent sulphur, and a mottled fracture at 0.30 per cent sulphur. The contraction of white cast iron is usually considered to be $\frac{16}{64}$ in. per ft. An increase in graphite indicates a decrease in contraction due to the swelling action of the metal when graphite is produced from the decomposition of iron carbide from the reaction $Fe_3C = 3Fe + C$ (graphite).

Chill Tests

59. Figs. 22, 23, 24 and 25 show the fractures of the chill test bars.

Depth of Chill

60. Depth of chill of the first casts from both series of heats decreased as the sulphur content increased. Since the manganese content also was decreasing with an increase in sulphur content, the decrease in chill was probably due to the decrease in total manganese content, together with a decrease of manganese not

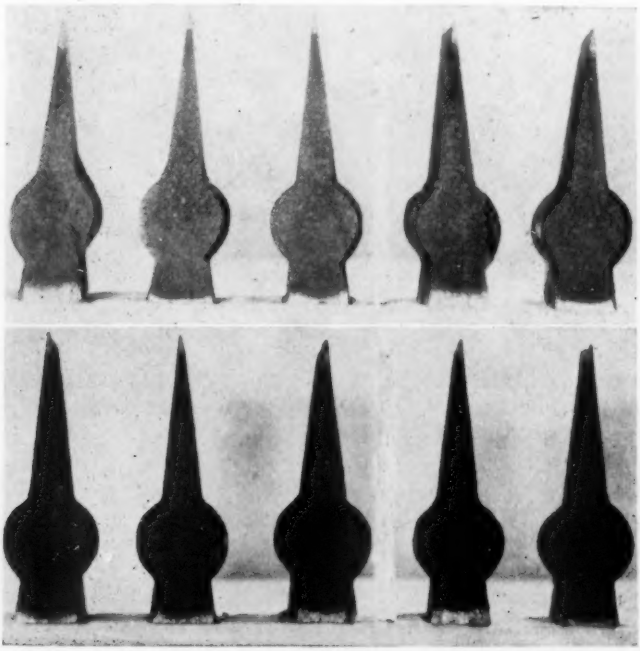


FIG. 23—FRACTURE OF CHILL TEST BARS — SERIES A — SECOND CASTS

TOP					
Cast Number	19	25	27	17	23
Sulphur, Per Cent.....	0.014	0.047	0.056	0.086	0.111
Manganese, Per Cent.....	1.57	1.58	1.68	1.48	1.69
BOTTOM					
Cast Number	21	29	13	11	15
Sulphur, Per Cent.....	0.144	0.147	0.152	0.161	0.163
Manganese, Per Cent.....	1.63	1.56	1.56	1.23	1.45

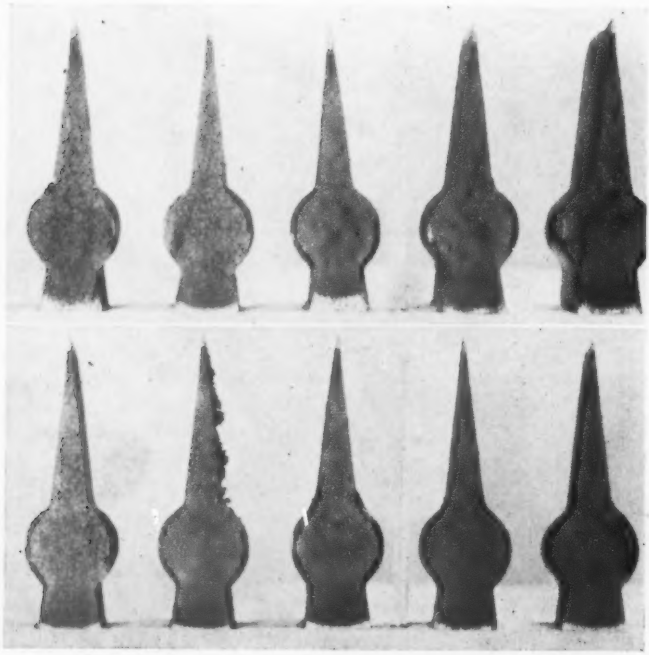


FIG. 24—FRACTURE OF CHILL TEST BARS — SERIES B — FIRST CASTS

TOP					
Cast Number	38	30	46	44	32
Sulphur, Per Cent.....	0.027	0.097	0.110	0.14	0.172
Manganese, Per Cent.....	0.85	0.85	0.82	0.87	0.85
BOTTOM					
Cast Number	48	34	36	42	40
Sulphur, Per Cent.....	0.207	0.281	0.295	0.36	0.500
Manganese, Per Cent.....	0.66	0.81	0.80	0.73	0.70

combined with sulphur. There seemed to be a rapid decrease in chill between 0.10 per cent and 0.18 per cent sulphur as compared to the rest of the casts.

61. Chill test bars 24 and 46, upon first appearance, seemed to have more chill than other casts of nearly the same analyses. A close examination showed that these deep chills were not wholly cementite but contained some graphite flakes.

62. The chill test of the second casts from both series of heats showed that an increase in manganese content for casts having less than 0.18 per cent sulphur caused an increase in chill.

Casts having more than 0.18 per cent sulphur decreased in depth of chill with an increase in sulphur content.

Transverse Strength

63. Transverse strength decreased as the sulphur content increased up to about 0.18 per cent. This is contrary to the results obtained by Coe[15] who believes that sulphur increases the transverse strength and hardness. A further increase in sulphur content raised the transverse strength slightly. As the transverse strength decreased with an increase in sulphur, the fracture showed

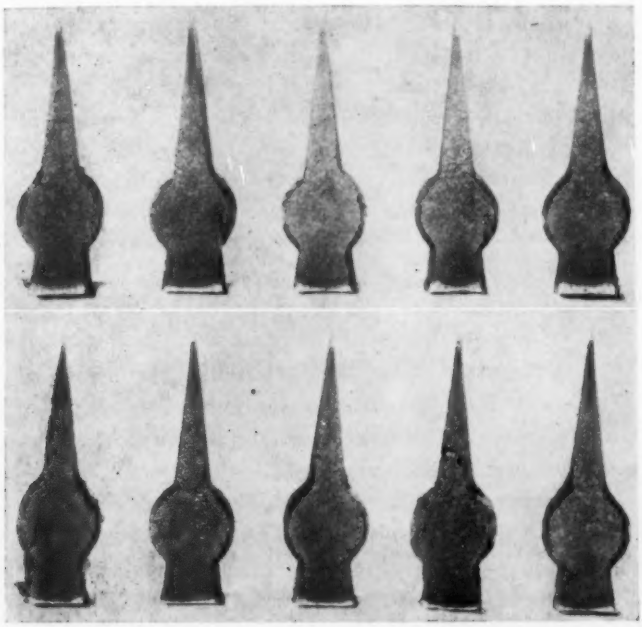


FIG. 25—FRACTURE OF CHILL TEST BARS—SERIES B—SECOND CASTS.

TOP					
Cast Number	39	31	47	45	33
Sulphur, Per Cent.....	0.028	0.095	0.109	0.139	0.170
Manganese, Per Cent.....	0.91	0.89	0.90	0.92	1.01
BOTTOM					
Cast Number	49	35	37	43	41
Sulphur, Per Cent.....	0.203	0.241	0.277	0.289	0.332
Manganese, Per Cent.....	0.94	1.09	0.97	0.81	0.74

larger graphite flakes, the maximum size of graphite flakes being found at about 0.18 per cent sulphur.

64. This change in the amount of graphite flakes was further checked by chemical means. Cast number 38, containing 0.027 per cent sulphur, had 3.05 per cent graphitic carbon and 0.49 per cent combined carbon. Cast number 30, containing 0.097 per cent sulphur, had 2.95 per cent graphitic carbon and 0.54 per cent combined carbon. Cast number 32, containing 0.172 per cent sulphur, had 3.20 per cent graphitic carbon and 0.38 per cent combined carbon. Cast number 42, containing 0.36 per cent sulphur, had 2.56 per cent graphitic carbon and 0.85 per cent combined carbon. Above 0.18 per cent sulphur, the microstructure becomes more mottled and the graphite flakes take a whorl or rosette form which would account for the slight increase in the transverse strength. It should be noted that the change in the graphitic structure with an increase in sulphur content is similar to that shown by Boyles[16]. Several of the transverse test bars above 0.26 per cent sulphur were defective as noted on the curves.

Machinability

65. The machinability of the cast iron decreased with an increase in sulphur content up to about 0.10 per cent of sulphur and then increased as the sulphur content increased up to about 0.18 per cent sulphur. An increase in sulphur beyond 0.18 per cent decreased the machinability rapidly. This increase in machinability with an increase of sulphur from 0.10 per cent to 0.18 per cent, is contrary to what is generally believed to be the case. At first, this phenomenon was thought to be due to the decrease in manganese content, but a cross check shows that, even with an increase in manganese content, in the second casts, the machinability tends to be better at about 0.18 per cent sulphur. The machining time increased when the manganese content was increased in the second casts as compared to the machining time for the same sulphur content of the first cast.

66. The machining time curve and the contraction curve are nearly identical in shape. An increase in contraction indicates a decrease in machinability and vice versa. As already mentioned, the cast iron showed large graphite flakes at 0.18 per cent sulphur.

67. Since the machinability of cast iron is often considered to be in direct relation to the hardness, it is interesting to note the hardness of the step bar, as measured next to the drilled hole, follows the hardness curve as taken from the tensile bars and is not in relation to machinability below 0.18 per cent sulphur.

Brinell Hardness and Tensile Strength

68. The Brinell hardness and tensile strength of both series of casts showed a definite decrease as the sulphur content was increased up to about 0.18 per cent. Above this point these two properties increased slightly. The curves representing these two properties have the same shape, showing that tensile strength is in proportion to hardness. The second casts for both series *A* and *B* showed an increase in Brinell hardness and tensile strength as compared to the first casts of the same analyses. This was caused by the manganese additions in the second casts. It also should be noted that nearly every time the manganese content increased or decreased the hardness and tensile strength correspondingly increased or decreased. This might have been caused by the manganese carbide formed, which increased the pearlite in the metal and resulted in less graphite.

Blow Holes and Gas Pockets

69. A large number of blow holes or gas pockets were found in some of the test bar castings when they were broken. It was found that these blow holes were only in the bars in which there had been a large loss of manganese in the first casts from each heat, or in which a manganese addition had caused a decrease in sulphur content in the second cast of each heat. Most of these bars were over 0.18 per cent sulphur, with the exception of casts 16 and 48. Casts 16 and 48 were heats in which furnace trouble necessitated a longer melting time than usual and the resulting manganese content was lower than the average.

Balls of Metal in Gas Pockets

70. About 50 per cent of the gas pockets found in the high sulphur iron contained small, bright, round balls of metal. Some of these balls or shot were loose in the holes, while others were firmly attached to one side. The appearance of the balls attached to the side of the hole is shown in the photomicrograph, Fig. 26,

FIG. 26—FRACTURE IN CAST IRON WITH GAS BUBBLE, X 1¼.

reproduced from a Carl Zeiss catalogue.[17] Some of these holes contained more than one shot.

71. Some of the high sulphur castings showed, upon machining, small crescent-shaped holes indicating that a ball or shot was only partly formed.

72. These blow holes, with or without shot, did not occur throughout the entire casting. In nearly every case they were found about ⅛ in. in from the casting surface, independent of the casting thickness except that no balls were found in castings thinner than ½ in. These balls and holes were more noticeable near the top of the castings than at the bottom.

73. At first it was thought that these balls were formed when the metal was poured from the ladle into the mold. After studying the gating systems used and the position of the holes in the castings, it is doubtful if a ball could pass through the skim gate and secondary sprue of the step test bar mold or remain ⅛ in. from the surface in the open top chill test bar mold. Therefore, it was thought that these defects formed upon solidification of the metal in the mold. This was proved further by some of the step test bars showing small balls squeezed out of the cope side of the 2-in. section as shown in Fig. 27.

74. Microscopic examination of these shot or balls showed that the graphite flakes were finer and less numerous than the

graphite in the metal around the balls. The balls which were detached from the metal showed no manganese sulphide inclusions, while those attached to the metal were free from manganese sulphide inclusions, except at the point of attachment where an excess of inclusions was found. The mother metal around the gas pocket also showed excessive manganese sulphide inclusions.

75. Some of these defects near the top of the castings showed a slag material between the ball and the mother metal. Fig. 28 shows one of these balls at 100 magnification surrounded by a slag which seems to be composed of three constituents. Fig. 29, which is a photomicrograph of a ball about the same size as shown in Fig. 28, but found loose in a clean gas pocket, shows the graphite flakes are smaller in the former.

76. Time did not allow an analysis of these slag constituents by the acid treatment as outlined by Campbell and Comstock[18], but from their similarity to those identified by Wohrman[19] and the chemical analyses of the shot, the constituents are assumed to be manganese sulphide as they had the same color as the inclusions at the tail of the ball. The black constituent was yellowish gray before sulphur printing and black after one min. of treatment in 2 per cent sulphuric acid. The other constituent was laminated and probably was an iron-sulphide-manganese-sulphide eutectic. It should be noted that Wohrman's photomicrographs indicate a ball was being formed, although he does not mention it. The sulphur print of this specimen indicated excess sulphur in the metal around the ball, but none within the ball.

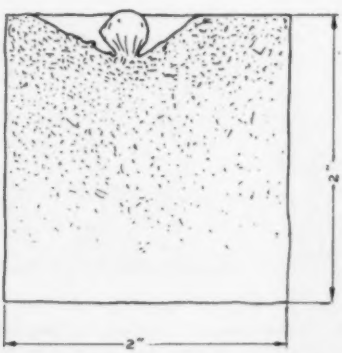


FIG. 27—BALL SQUEEZED FROM COPE SIDE OF CASTING DURING SOLIDIFICATION.

77. The corrected iron-sulphide-manganese-sulphide (FeS-MnS) diagram as given by McCance, which Wohrman[19] believes to be correct, shows the limit of solid solubility of manganese sulphide (MnS) and iron sulphide (FeS) at 60 per cent iron sulphide (FeS) and 40 per cent manganese sulphide (MnS).

78. Chemical analyses of these balls showed an average of 2.40 per cent carbon, 2.77 per cent silicon, 0.44 per cent manganese,

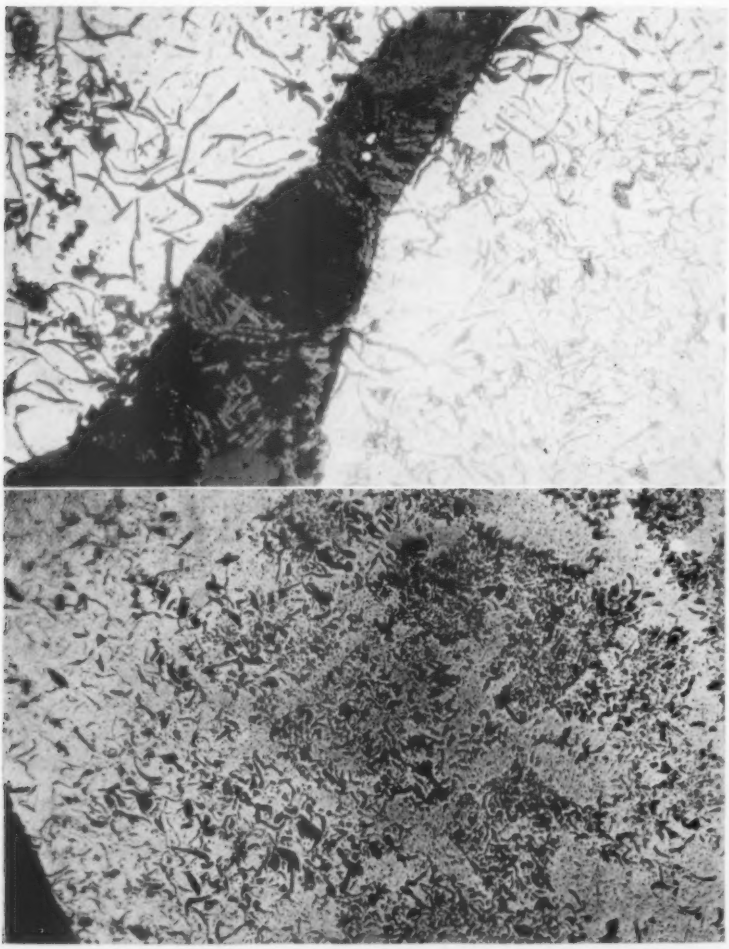


FIG. 28—TOP—SLAG BOUNDARY AROUND BALL IN ELECTRIC FURNACE CAST IRON. ETCHED 1 MIN. WITH 2 PER CENT SULPHURIC ACID, X 100. CAST NO. 20. SULPHUR, 0.171 PER CENT. MANGANESE, 0.98 PER CENT. FIG. 29—BOTTOM—BALL FORMED IN ELECTRIC CAST IRON GAS POCKET, UNETCHED, X 100. CAST NO. 20.

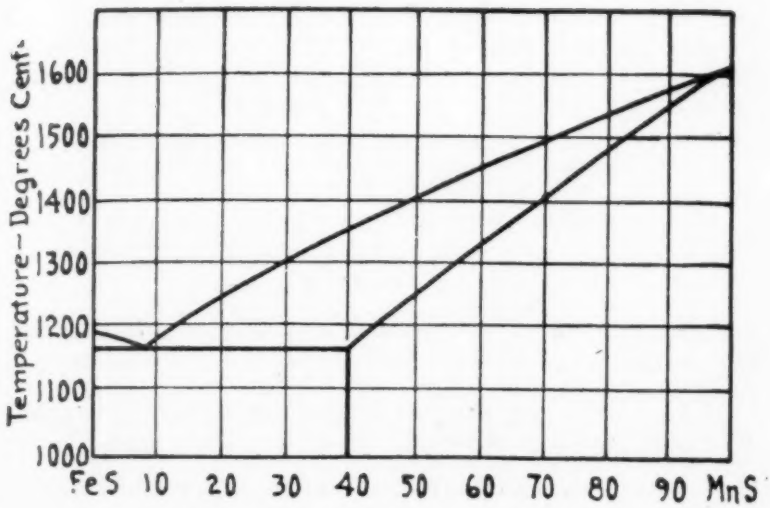


FIG. 30—THE CORRECTED FeS-MnS DIAGRAM AS GIVEN BY MCCANCE.

0.03 per cent sulphur and 0.24 per cent phosphorus. These analyses would indicate that the balls, upon forming, changed the analyses as compared to the mother metal. This change in analyses being: carbon and manganese decreased 33 per cent; sulphur decreased 90 per cent; and phosphorus increased 100 per cent. The analyses indicated no change in the silicon content. Some of the balls upon being hammered were found to be more malleable than the mother metal.

Hypothesis on Formation of Balls of Metal in Gas Pockets

79. The formation of these balls and gas pockets seemed to be caused by the manganese sulphide as they were not found in castings which did not contain manganese sulphide. An hypothesis might be suggested to explain their occurrence.

80. *Hypothesis:* Manganese sulphide acts as a flux or a purifier which cleanses the metal of gas and forms the shot. A clean bright ball of metal can form only when a fluxing action is present. The fluxing action would account for the lower carbon and sulphur analyses of the ball as compared to the mother metal. The manganese sulphide tends to increase the surface tension which accounts for squeezing of the balls from the surface of the metal.

81. This fluxing action of manganese sulphide may account for the common belief that sulphur causes blow holes in cast iron. This, as shown in Fig. 30, indicates that the solidus temperature for manganese-sulphide-iron-sulphide (MnS-FeS) compounds containing over 60 per cent iron sulphide (FeS) is about 1160°C. (2120°F.) which is the same temperature at which dripping of the slag and metal from the thermocouple ceased.

CONCLUSIONS

82. The test results obtained from this investigation indicate that:

1. There is a transition point at about 0.18 per cent sulphur where the properties of electric furnace cast iron change rapidly.

2. Up to about 0.18 per cent sulphur, an increase in sulphur will lower the transverse strength, tensile strength and hardness, and will increase the transverse deflection.

3. Above about 0.18 per cent sulphur, an increase in sulphur will increase the transverse strength, tensile strength, and hardness, and will decrease the transverse deflection.

4. An increase in sulphur content will decrease the resulting manganese analysis, the decrease being more rapid in iron containing more than 0.18 per cent sulphur.

5. An increase in sulphur content will not affect the depth of chill if the manganese content is held constant.

6. The flowability of the iron decreases very rapidly at about 0.18 per cent sulphur. Below and above this transition point an increase in sulphur will not change the flowability if the manganese is held constant.

7. An increase in sulphur content up to 0.14 per cent will decrease the machinability of the cast iron. A further increase up to 0.18 per cent will increase the machinability. Above this transition point, the machinability will decrease rapidly.

8. An increase in sulphur content up to 0.14 per cent will increase the contraction of the cast iron. A further increase up to 0.18 per cent will decrease the contraction. Above this transition point, the contraction will again increase.

9. An increase in sulphur over about 0.18 per cent will tend to produce blow holes or gas pockets in electric furnace cast iron.

10. An increase in manganese content will increase tensile strength, transverse strength, hardness, depth of chill and will decrease transverse deflection and machinability.

11. Sulphur, up to about 0.18 per cent in electric furnace cast iron of the compositions used in this investigation, is not very detrimental to the properties of the iron.

ACKNOWLEDGEMENTS

The authors wish to take this opportunity to express their appreciation to the following persons who assisted in conducting and presenting this investigation: Herbert Scobie; Adrian Den Breejen; Carl Wood; Frank Brey; Professors J. R. DuPriest, C. A. Koepke, T. P. Hughes, and H. S. Jerabek; and Misses Carrie H. Green and Fannie Hall. Assistance in the preparation of some of the tests was furnished by personnel of the Works Progress Administration Official Project Number 65-1-71-140, Sub-project Number 293.

Bibliography

1—Moldenke, Richard, *"The Principles of Iron Founding,"* McGraw-Hill Book Co., New York (1930).

2—Evans, George S., *"Desulphurizing Cupola Iron with Fused Soda Ash,"* THE FOUNDRY (1934), May, pp. 26-27, 62, 64.

3—Girardet, L. F. and Lelievre, R., *"Desulphurization of Cast Iron and the Action of Sodium Carbonate on Molten Cast Iron,"* CHEMICAL ABSTRACTS (1933), vol. 27, part 1.

4—Bettendorf, C. and Wark, N. J., *"The Desulphurization of Steel and Pig Iron,"* CHEMICAL ABSTRACTS (1933), vol. 27, part 1.

5—Moldenke, Richard, *"The Principles of Iron Founding,"* McGraw-Hill Book Co., New York (1930), p. 52.

6—A.S.T.M. Designation: A 46-24 *"Standard Specifications for Chilled Car Wheels,"* A.S.T.M. STANDARDS 1933, pp. 471-475.

7—Hurst, J. E., *"Metallurgy of Cast Iron,"* Sir Isaac Pitman & Sons, Ltd., London (1926).

8—Smith, E. K. and Riggan, F. B., *"The Effect of Sulphur on the Physical Properties of Gray Iron,"* TRANS. A.S.T.M. (1928), vol. 28, pp. 205-217.

9—Holtby, Fulton, *"Rapid Temperature Measurements of Cast Iron with an Immersion Thermocouple,"* TRANS. A.F.A. (1939), vol. 47, pp. 854-872.

10—A.S.T.M. Designation: A 124-29 *"Standard Specifications for the Arbitration Test Bar and Tension Test Specimens for Cast Iron,"* A.S.T.M. STANDARDS 1933, part 1, pp. 496-498.

11—Saeger, C. M., Jr., and Krynitsky, A. I., *"A Practical Method for Studying the Running Qualities of a Metal Cast in Foundry Molds,"* TRANS. A.F.A. (1931), vol. 39, pp. 513-540.

12—Herty, C. H., Jr., and True, O. S., *"Reaction Between Manganese and Iron Sulphide,"* TRANS. A.I.M.E., vol. 71, pp. 540-548.

13—Rohl, G., *"The Constitution of the Sulphide Enclosures in Iron and Steel and the Desulphurization Process,"* Carnegie Scholarship Memoirs, IRON AND STEEL INSTITUTE (1912), vol. IV.

14—Shaw, John, *"Some Gray Iron Problems,"* TRANS. A.F.A. (1926).

15—Coe, H. E., *"Influence of Sulphur on Cast Iron,"* JOURNAL CHEM. IND. (1913), vol. 32.

16—Boyles, Alfred, *"The Freezing of Cast Iron,"* TRANS. A.I.M.E. (1937), vol. 125, pp. 141-203.

17—Zeiss, Carl, Inc., Zeiss Advertising Catalogue, Mikro 500, New York, New York.

18—Campbell and Comstock, AMERICAN SOCIETY FOR METALS, *"Metals Handbook,"* Cleveland, Ohio (1936).

19—Wohrman, C. R., *"Inclusions in Iron,"* American Society for Steel Treating, Cleveland, Ohio (1928).

DISCUSSION

Presiding: G. P. PHILLIPS, International Harvester Co., Chicago, Ill.

MR. HOLTBY: I do not know whether any of you gentlemen would do what we have tried in the last three weeks. We are actually adding sulphur to our cast iron now to increase machinability in the machine shop to keep them from saying the castings are too hard. That has been in practice now for three weeks at the University.

W. H. SPENCER[1]: Have you tried the effect of manganese balance with the sulphur in your work? That is just a suggestion there. I noticed you had about 0.82 per cent manganese with your 0.18 per cent sulphur, which is approximately four times the sulphur. Some work has been done which has not been reported along that line of holding the sulphur constant and varying the amount of manganese. Starting with a ratio of 3.5 of manganese to sulphur, if the manganese is increased hardness will result, if it is decreased softness will result. When you drop below the manganese ratio, you get hardness again.

Have you planned to vary the manganese?

MR. HOLTBY: In some of our later work done in the last year we have tried that. We cross-plotted our curves taking certain sulphur

[1] Manager Foundry Div., Wilkening Mfg. Co., Philadelphia, Pa.

points and catching certain manganese points. We found that manganese does increase the tensile strength of the cast iron.

We have run some tests to check this work where we have taken and multiplied the sulphur analysis by 1.7 and added 0.35 per cent manganese. That figure has been used in Minnesota for a long while as being a typical manganese analysis. In other words, 1.7 times sulphur plus 35 points as a safety factor.

We have found the same condition occurred; that manganese was or could be considered as a hardener to increase the tensile strength. Sulphur acted about the same way as Mr. Spencer has said. If we lower manganese too far, the sulphur is going to take up all the manganese as manganese sulphide, the theoretical ratio there being 1.7 to 1 and we again consider that the sulphur did start to act as a hardener.

G. F. COMSTOCK[2]: I am interested in the photomicrographs showing the effect of changes in sulphur on graphitization. I wonder if the author found it generally to be the case that increasing sulphur tended to change the graphite from the eutectic form, as shown in Fig. 18, to the coarse flake form as shown in Fig. 19.

MR. HOLTBY: Yes. These are just typical photomicrographs that we tried to show, typical structures which in some cases, especially Figs. 20 and 21, I believe are quite unusual. The structure of Fig. 18 is fairly typical.

MR. COMSTOCK: The statement in your paper which seems to require further explanation is paragraph 67. In Fig. 15, as well as Fig. 11, the curves for hardness and machining time could be drawn so as to be practically parallel with the single exception of the first point referring to the very low sulphur iron. The reason for the discrepancy in that iron is very logically given in your Fig. 18 where it is shown that with very low sulphur, the type of graphite is different. We found this same effect of sulphur in some of our work, namely, that it tends to change the fine eutectic graphite into a normal flake form. This effect of sulphur on the graphite structure was first described by Alfred Boyles in 1937.* We also found that with the fine eutectic graphite machinability is much better, although hardness may be greater. Your results, therefore, check our experience in a very interesting way but it does not appear from your paper that these points were appreciated.

MR. HOLTBY: We feel that first point would indicate a little higher hardness due to the fact that there must be more free manganese acting in the form of manganese carbide to harden up the iron. Why that machines so readily as compared to the same iron with 0.10 or 0.11 per cent sulphur we do not know.

Those curves have been checked. We have run triplicate heats on every one of them and as the curves are illustrated, they are just

[2] Metallurgist, Titanium Alloy Mfg. Co., Niagara Falls, N. Y.

* "*Freezing of Cast Iron*," A. I. M. E., No. 809, (1937).

one series. We have no explanation as to why machinability was so much better at that point.

One thing I would like to call attention to, is that the contraction curve and the machinability curve are similar in shape, Figs. 10 and 11. In other words, at certain points where contraction was more, machining time went up very rapidly and vice versa.

At the present time, we are running a series of tests trying to correlate the difference between machining time as tested by this method and actual contraction of the cast iron.

There may be some question raised as to our method of measuring machinability, but as I mentioned, it is an inexpensive method and can readily be set up as compared to a $5,000 machine which is sometimes used for machinability tests.

CHAIRMAN PHILLIPS: I find that the deflection curves are of real interest—the fact that you get increasing deflection up to at least 0.30 or 0.35 per cent sulphur.

I noticed that in some cases in which the bars were defective, you were not able to continue the curves, but the fact that deflection increases up to 0.30 per cent with apparently no change in the transverse strength, would indicate that impact resistances improve, too. That is something on which I presume you did not do any actual testing.

MR. HOLTBY: At the present time the impact bars are being machined. It is a long, tedious process to grind all these down. There are approximately 1,500 test bars that will have to be ground down for the complete series. No impacts have been run at the present time, but we are running our impacts primarily because of that curve.

Those bars shown as defective on the curve sheets, were discarded because there were so many round shot rolling out of the casting that we could not figure out what the cross-section area of the bar was, so we scrapped them rather than try to give any data on the transverse strength.

There was only one of all our tensile bars that failed due to shot, and that was the fact that it broke in the thread of the testing machine. In other words, all these shot occur at about an eighth of an inch from the surface, so after the tensile test bars were machined, they were free from shot.

Crucible Melting with Modern Gas Burners

By F. L. Wolf*, Mansfield, Ohio.

Abstract

Operating results are presented for an insulated, stationary, No. 60 crucible furnace using natural gas and melting a variety of non-ferrous alloys. Modern burner equipment allows a considerable saving in gas, with greater melting speed and increased crucible life. A truly neutral atmosphere is obtained without requiring any skill on the part of the operator. The flame temperature is higher and the service is severe on refractories even though they are of the super-duty type.

1. At the 1939 A.F.A. convention in Cincinnati, a paper[1] was presented covering the fundamentals which apply to crucible melting. The writer has had the opportunity to review the paper by E. W. Williams[2], which covers the subject more thoroughly than is intended in this instance.

2. The present paper is intended to report some preliminary tests on a modern and efficiently-insulated, stationary, crucible furnace (No. 60 crucible) and to deal very briefly with a users reaction, after a limited experience, with this type of equipment. Various non-ferrous alloys were melted.

Furnace Lining

3. The lining used consisted of 3-in. of a preformed and prefired facing of a sillimanite material backed with 3¼-in. of a lightweight concrete—an air setting refractory concrete, good up to

---

* Technical Director, Ohio Brass Co.

[1] Eggleston, G. K., "*Efficiency in Crucible Melting*," Transactions, American Foundrymen's Association, vol. 47, pp. 450-468 (1939).

[2] Williams, E. W., "*Improvements in Gas Melting Furnaces in the Non-Ferrous Foundry*," A.F.A. Preprint 40-17 (1940).

Note: This paper was presented at a Non-Ferrous Session of the 44th A.F.A. Convention, May 7, 1940, Chicago, Ill.

about 2100°F., in which the grog was granules of light-weight refractory. The furnace was further insulated with ¾-in. of asbestos cement between the shell and the insulating concrete.

4. The furnace bottom was rammed in place and was not as satisfactory as we feel a prefired block would be. Covers and base blocks, or stools, were of firebrick, but it appears that firebrick is not good enough for the lining of such a unit.

5. In view of the popularity of silicon-carbide linings, the next installation is to be of this material backed with 4½-in. of light-weight refractory insulation rated for 2600°F.

Burners

6. The burner equipment is like that described by Williams[2]. Two burners are employed, as will be seen from Fig. 1, and the center line of the burners is at the junction of crucible and base block. The alloy tips at the mouth of the burners are drilled to 1⅞-in. diameter. The two governors or reducers, may be seen in Fig. 1. The first reduces the gas pressure from 8 to 4 oz. and the second reduces the pressure to zero. Since the gas is billed at 8 oz. pressure, the meter reading (at 8 oz.) is used without correction to zero pressure. The gas has a calorific value of 1000 B. t. u. per cubic foot.

7. The inspirator-type, proportional mixer was furnished with several orifices (or gas ports). The orifice adopted after some experimentation was ⅜-in. in diameter.

8. Air at 16 oz. pressure is supplied by a turbine. There are valves for controlling both air and gas but in practice, the gas valve is wide open and the heat input is regulated with the air valve. Generally, both valves are wide open.

Combustion Space

9. Since a standard No. 60 crucible is 11$\frac{11}{16}$-in. at the bilge, the lining was made 15-in. inside, which was the minimum diameter which would allow the introduction of the lifting tongs when a new crucible was used in the new furnace. The resultant combustion space was 13$\frac{13}{16}$-in. at the smallest point. The lining wore ½-in. all around in the period during which records are available.

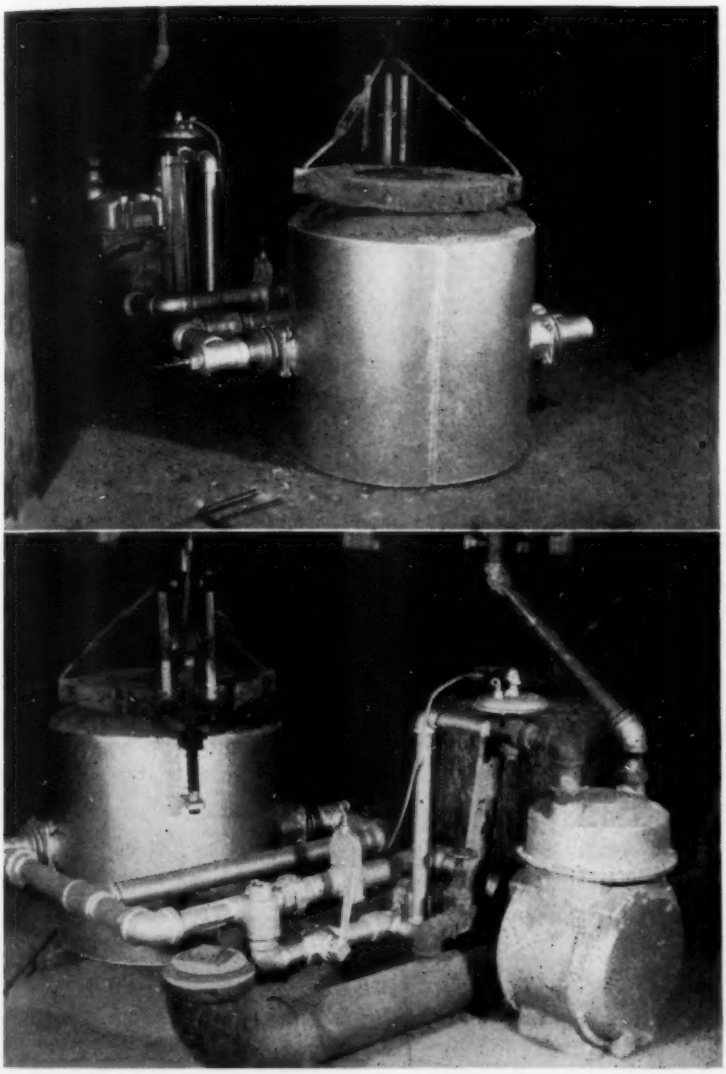


FIG. 1—TOP—FRONT VIEW AND BOTTOM—REAR VIEW OF BURNER EQUIPMENT USED ON FURNACE.

Analysis of Atmosphere

10. Gas analyses made with the Orsat apparatus shows that a truly neutral atmosphere may be obtained with the new burners, as shown in Table 1.

Table 1

ANALYSES OF FURNACE ATMOSPHERE

Furnace	*Determinations*	*Pressure of Burners In. of Water*	*Gas Analysis, Per Cent* CO_2	*CO*	O_2
New	1	8¼	12.3	none	none
	2	8¼	11.9	none	none
	3	6	11.9	.3	none
	4	4	10.6	.8	1.0
Old	1	.	9.3	.9	3.0
	*2	.	8.6	1.0	4.4

* Deliberately "oxidizing."

11. The percent of carbon dioxide is lower than is obtained when coal is burned efficiently in a boiler; this is because the products of the combustion of natural gas are not all gaseous but consist of carbon dioxide and water, while coal contains much carbon which burns to carbon dioxide.

12. For the combustion of pure carbon, we have the reaction:

$$\underset{1 \text{ volume}}{C} + \underset{}{O_2} = \underset{1 \text{ volume}}{CO_2}$$

If air is 20 per cent oxygen, the oxygen carries with it 4 volumes of nitrogen and we also have 4 volumes of nitrogen in the flue gas. Thus it would be possible to have the same percentage of carbon dioxide in the flue gas as we had oxygen in the air, namely, 20 per cent carbon dioxide.

13. If we assume natural gas to be 100 per cent methane (which lacks 15 per cent of being strictly true), the combustion may be expressed by the equation:

$$\underset{1 \text{ volume}}{CH_4} + \underset{2 \text{ volumes}}{2O_2} = \underset{1 \text{ volume}}{CO_2} + 2H_2O$$

In this case, the oxygen is accompanied by 8 volumes of nitrogen as is the CO_2 in the flue gas. One volume (of CO_2) out of a total of 9 in the flue gas gives 11.1 per cent CO_2 which checks (probably too closely) with what was obtained by analysis.

Neutral Atmosphere

14. The gas analyses shows that we have a neutral atmosphere with the new burners and a slightly oxidizing atmosphere, to give the most rapid melting, with the old burner. It was found

that the neutral atmosphere was all right for melting an aluminum bronze which heretofore had given best results when a slightly oxidizing atmosphere was used. Incidentally, when the slag was pushed back the metal was seen to have a shiny appearance under the neutral atmosphere.

Gas Consumption

15. Under the most favorable conditions, the equipment has melted 150 lb., pouring temperature 2080°F., in 27 min. The gas consumption was 270 cu. ft. or at the rate of 180 cu. ft. per 100 lb. of metal.

16. The furnace was favored for several days in order that it might be run at maximum efficiency, but the unit was run under conditions of foundry operation during the greater part of the time during which the data in Table 2 were obtained.

Table 2

DATA ON FURNACE OPERATION

Heats	414
Average Charge per Heat, lb.	135
Metal Temperature, °F.	+2150
Lb. Melted	55,869
Cu. Ft. Gas Used	167,880
Cu. Ft. Gas per 100 lb. Melted	300

17. There would have been further data on gas used but, after the burner tunnels partially failed, the furnace was used less than formerly and a considerable quantity (about half of the total) of tin and lead was melted for casting into small pigs to make weights. It is difficult to evaluate the gas required for the white metals.

18. The gas consumption has been equaled with the old equipment under favorable, or "furnace test," conditions but the new burners will allow this low gas consumption under foundry operating conditions.

OPERATING NOTES

19. It was immediately noticed that the new equipment made much less noise than the old single burner units. This is entirely reasonable in view of the fact the velocity is much less as we have two flames instead of one.

20. The new lining, being better insulated than the old, which consisted of 4½-in. of fire brick backed with 1-in. of sil-o-cel powder, would be expected to keep the steel shell much cooler. Such was found to be the case but the shell, though measurably cooler than on the old furnaces, was too hot to allow any but the briefest contact of the hand with it.

21. The insulating value obviously was superior with the new unit but the temperature gradient also was much steeper. With the old furnace, it is possible to distinguish objects on the furnace bottom immediately after pulling a crucible, but with the new unit, the furnace was at such a dazzling white heat that objects could not be distinguished with the naked eye. No actual figures are available, but the temperatures are high.

22. The high flame temperature is probably responsible for the faster melting which characterizes the equipment. The same speed should be attainable with poor utilization of heat as with a more economical set-up, provided the flame temperatures are the same, if the input can be made sufficiently high to offset the heat losses. It takes a superior refractory to stand this service and, compared to the old units, the service is severe. Trouble was encountered with the burner tunnels, particularly.

23. One important factor is that once set, the furnace will operate with an absolutely neutral atmosphere without any regulation or adjustment.

24. The melting speed of the new equipment is greater than that of the old, but the difference is not so great as is the case with the gas consumption. It will be noted that the average charge per heat is low, showing many sub-capacity heats. Conservatively, an extra heat a day may be expected.

25. Crucible life is benefited materially, but just what the final percentage increase will be, is difficult to say at this writing. The crucible units are not used as steadily as in former days and the average crucible life is considerably below what it was when the crucible furnaces were being pushed each day.

CONCLUSIONS

26. Use of modern gas burners gives a quietly-operating, stationary, crucible furnace in which perfect combustion and

a truly neutral atmosphere is attained. The flame temperature is high and the service is severe even for super-duty refractories. Ordinary fire clay will not stand up.

27. As a result of perfect combustion and good insulation, attractive gas savings are possible. Figures as low as 180 cu. ft. per 100 lb. of metal are obtained for the No. 60 crucible charged with 150 lb., under the most favorable conditions. Under production conditions, the gas consumption averages 300 cu. ft. per 100 lb.

28. While the gas savings is the most important factor, melting is faster, to the extent of an extra heat a day, and crucible life is improved.

29. Flame control is perfect without adjustment by the furnace tender, as control is vested in one valve.

DISCUSSION

In the absence of the author, this paper was presented by R. W. Parsons, Ohio Brass Co., Mansfield, Ohio.

Presiding: W. J. LAIRD, Westinghouse Electric and Manufacturing Co., East Pittsburgh, Pa.

W. B. GEORGE[1]: Mr. Parsons, you made reference to the loss of 2 per cent zinc in a neutral atmosphere. You thought there was some oxidizing condition going on. Is that correct?

MR. PARSONS: We had a loss of 2 per cent zinc in a CO_2 atmosphere which most definitely is *not* neutral—if it were, it would not oxidize zinc. In several places, the paper mentions that a neutral atmosphere was obtained whereas, actually, perfect combustion was obtained instead.

W. B. GEORGE: Zinc can be lost in any atmosphere by distillation.

MR. PARSONS: Certainly, but if you are trying to make 85-5-5-5 you compensate for such distillation losses so that you will obtain 5 per cent zinc. The experiment mentioned was conducted under operating conditions with compensation made for any normal loss, and with a CO_2 atmosphere maintained over the metal for the entire day, there was an additional 2 per cent loss in zinc—the alloy having 2 per cent less zinc than usual. (The atmosphere was maintained in a low-frequency induction furnace which normally operates without being influenced by products of combustion since the heating is electric.)

W. B. GEORGE: Can the loss due to the atmosphere and not distillation be explained?

[1]Metallurgical Engineer, R. Lavin & Sons, Chicago.

MR. PARSONS: You get the distillation right along, whether the atmosphere be one consisting of CO_2 or otherwise. The loss was over and above the normal loss for which we compensated.

W. B. GEORGE: Will you explain how it is lost if not by distillation?

MR. PARSONS: The loss was caused by the oxidizing effect of the carbon dioxide on the zinc. When you use a zinc reductor in the chemical laboratory the (iron) oxides are reduced; the same thing happens in this case, zinc reduces CO_2 or, putting it another way, CO_2 oxidizes zinc. The test was under operating conditions and there were no differences, such as temperatures, other than the CO_2 atmosphere on one furnace. The makers of CO_2 gas have tried maintaining CO_2 atmospheres over galvanizing kettles with the same results—loss of zinc through oxidation by the CO_2 gas.

CHAIRMAN LAIRD: I can appreciate that it would be very difficult to tell in zinc losses whether zinc was lost by distillation or by oxidation. How did you determine whether the 2 per cent was lost by distillation or by oxidation?

MR. PARSONS: It should distill just as well with CO_2 or without it. I cannot conceive of the presence of CO_2 making it distill any better.

CHAIRMAN LAIRD: The author compensated for the normal losses he would have suffered in normal melting, but in this particular case, with a blanket of CO_2 the losses were 2 per cent greater than the normal volatization. Would not there be some justification for believing that the losses were due to oxidation rather than to volatization?

MR. PARSONS: A great deal of work has been done to show that CO_2 is definitely oxidizing in the heat treatment of steel, it should be just as oxidizing over molten brass as in a heat-treating furnace. If the CO_2 atmosphere were dry, the oxidation might not be so pronounced, but in a gas-fired, heat-treating furnace, the atmosphere is not dry and the steel is scaled by the carbon dioxide gas.

W. B. GEORGE: The atmosphere over the bath doesn't affect the metal but little with proper coverage.

H. J. ROAST[2]: Mr. Chairman, I'd like to say that it seems such a very obvious thing that if you have a constant condition and all you do is add CO_2 atmosphere and it increases the loss 2 per cent, then it is clear indication that with this CO_2 vapor, something of zinc is lost.

Personally I quite agree with the oxidation theory, but in any case more was lost with CO_2 than without.

[2]Vice President, Canadian Bronze Co., Ltd., Montreal, Que., Canada.

Measuring the Tendency of Some Cast Irons to Seize Under Sliding Friction

By A. H. Dierker†, Bernard Fried*, and H. H. Dawson*,
Columbus, O.

Abstract

Seizure of cast iron in lubricated systems is due to local temperatures and pressures becoming so high that there is a momentary failure of the oil film, and particles of the contacting materials are actually welded together. At the Ohio State University's laboratory, tests were conducted for measuring resistance to seizure of metal surfaces in sliding contact, in terms of the pressure between the surfaces at seizure. The test is run by sliding a specimen, to which a load is applied, against a fixed block. Motion is imparted to the specimen through the arm of a shaping machine. The testing apparatus is described and illustrated in detail. The testing procedure followed in making tests with this machine is also explained and gives valuable data on both curved and flat surfaced specimens which were used in this investigation. The results show that, although no correlation between seizure resistance and microstructure has been made, large amounts of carbides or ferrite are not desirable in specimens; also since no relationship between Brinell hardness and the tendency of materials to size has been found, seizure is not likely to be avoided by using harder materials.

Introduction

1. Metal surfaces which operate against each other, in sliding contact under load, are potentially subject to seizure. Seizure is due to local temperatures and pressures becoming so high that there is a momentary failure of the oil film, and particles of material are actually welded to the contacting surfaces.

2. The desirability of developing a test to rate material in the order of their resistance to seizure has been generally recognized, and a number of tests have been designed for this purpose.

† Research Engineer, Engineering Experiment Station, Ohio State University.
* Research Staff, Engineering Experiment Station, Ohio State University.

Note: Presented before the Gray Iron Session, 44th Annual A. F. A. Convention, Chicago, Ill., May 10, 1940.

Practically all tests are conducted under conditions of either complete (flooded) lubrication or no lubrication between the contacting surfaces. In the majority of cases, ratings of the materials are based on the length of operating time under a fixed load, before seizure occurs.

3. However, recent research work on lubrication problems[1**] has clearly demonstrated that before metal to metal contact (which precedes seizure) occurs, there is a very marked change in the nature of the lubrication between the mating surfaces. There is a transition from a state of complete lubrication to one of boundary lubrication, and it is only after rupture of the thin film of oil, which characterizes boundary lubrication, that seizure occurs. The difference between the two states of lubrication is so great that a discontinuity between them is suggested. In boundary lubrication, surfaces have the property of static friction and the frictional resistance varies inversely with the viscosity of the lubricant, while in complete lubrication there is no static friction and the frictional resistance varies directly with the viscosity of the lubricant. It seemed advisable, therefore, to conduct these tests under conditions of boundary lubrication and dispense with the camouflage of complete lubrication which could at best only complicate the problem unnecessarily.

4. The alternative of conducting tests without any lubrication was discarded due to the fact that lubricants produce changes in the metal surfaces and their surface properties; hence, an unlubricated surface is not representative of surfaces used in actual operating practice. Finally, the success obtained in resisting seizure by using extreme pressure lubricants would indicate that a rating of materials with respect to their resistance to seizure might more logically be based on the pressure between the surfaces at seizure, rather than on their length of operation under a fixed load. Jominy[2] showed the difficulty encountered in trying to duplicate results obtained in wear tests using a constant load. In this investigation a short series of tests were run at the laboratory using a constant load. Identical difficulties arose, and so it was not considered likely that a correlation between seizure resistance and length of operating time under a fixed load, could be made with any degree of confidence.

** Superior numbers refer to Bibliography at end of paper.

5. A test has been developed in the laboratory for measuring resistance to seizure of metal surfaces in sliding contact, in terms of the pressure between the surfaces at seizure. The motion between the surfaces is of the reciprocating type.

APPARATUS

6. The test is run by sliding a specimen, to which a load is applied, against a fixed, stationary block, motion being imparted to the specimen through the arm of a shaping machine. Essentially the apparatus consists of the block, the specimen, the block fixture and the device for measuring the frictional forces, the specimen holder and the loading device, and the shaper. The advantage of using a shaper in the development stage of these tests is at once obvious. First it gives the same type of motion encountered in practice and secondly, for experimental purposes, its flexibility in regard to length of stroke and range of speeds is very desirable.

Block Fixture and Friction Measuring Device

7. This unit is illustrated in detail in Fig. 1. K is a frame casting which is clamped into the shaper vise. G, the block holder, rides on two rows of ball bearings and is held in position by the two heavy steel springs, H. The block, B, is held in G with set-screws. The dial, J, measures the deflection of the springs, H, during the operation of the test and measures the friction between the block and specimen. (These readings were taken only during the

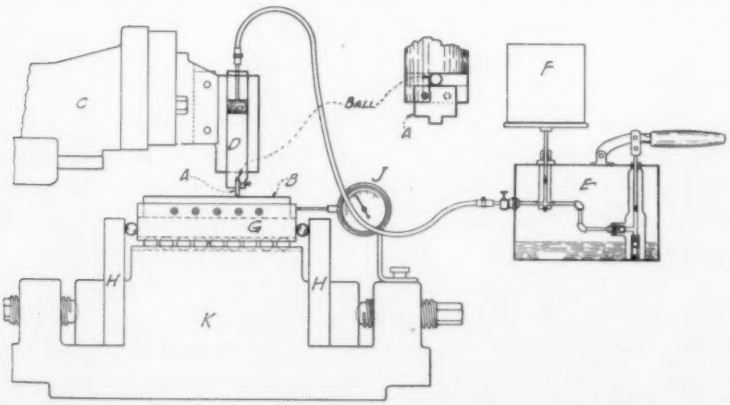


FIG. 1—SCHEMATIC DRAWING OF TESTING APPARATUS SHOWING IMPORTANT SECTIONS OF THE MACHINE. A—SPECIMEN; B—BLOCK; C—SHAPER HEAD; D—PISTON AND SPECIMEN HOLDER; E—HYDRAULIC LOADING SYSTEM; F—APPLIED LOAD; G—BLOCK SUPPORT; H—SPRING CLAMPS; J—DIAL GAUGE; AND K—FRAME CASTING.

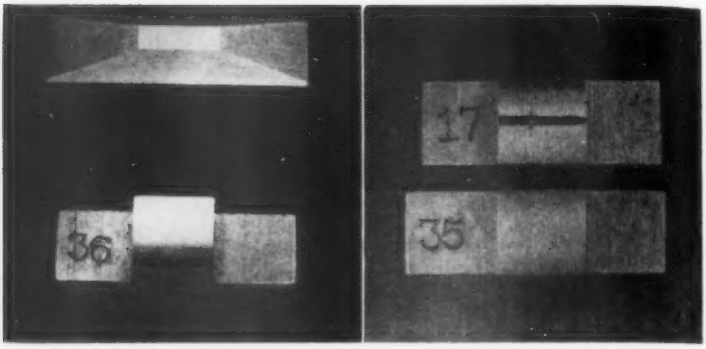


FIG. 2—FLAT SURFACED SPECIMEN (LEFT) AND CYLINDRICAL SURFACED SPECIMEN (RIGHT). CYLINDRICAL SPECIMEN (TOP) AFTER SEIZURE AND (BOTTOM) BEFORE SEIZURE.

preliminary tests and since they had no immediate bearing on the results they were discontinued for the sake of convenience in running the tests.)

Loading Device and Specimen Holder

8. Load pressing the specimen surface against the block is applied through a hydraulic system, E. The load is applied by adding weights to the piston, F, the load being transmitted through a pressure hose to a second piston, D, which rides in a housing, securely held in the clapper-box on the head of the shaper, C. The specimen, A, is held in piston D by a pair of set-screws, the face opposite the specimen test surface fitting snugly against a ½-in. steel ball in the center of the piston.

Specimens

9. The flat specimens, Fig. 2, had surfaces 0.0468 sq. in. in area and were ground flat on a surface grinder. After the specimens were clamped into operating position these surfaces were polished, first with No. 320 carborundum cloth and then with 3/0 emery paper.

10. Curved specimens in the earlier tests were first machine finished in a lathe to ¾-in. radii and then polished by hand with 3/0 emery paper. After preliminary tests proved the advisability of using curved sliders in these tests, all specimen surfaces were ground to constant radius (¾-in.) on a cylinder grinder, Fig. 3. Care was taken to keep the longitudinal feed and depth of cut the same on all specimens.

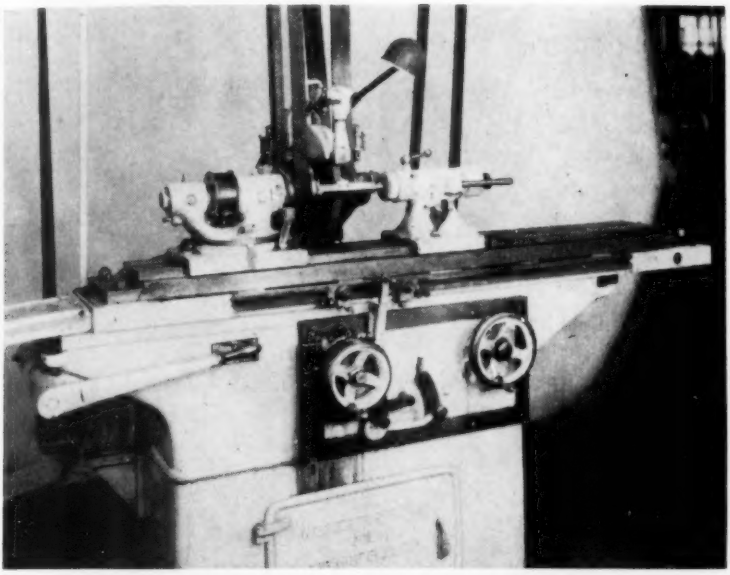


Fig. 3—Cylinder Grinder for Preparing Specimen Surfaces.

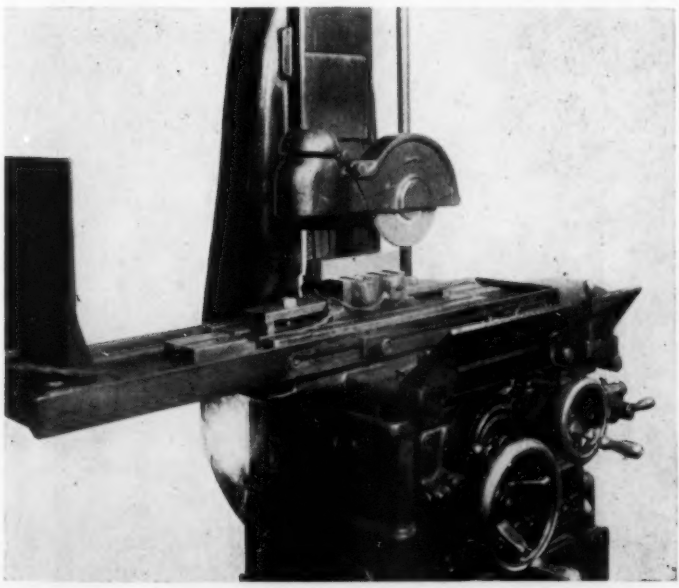


Fig. 4—Surface Grinder for Preparing Block Surfaces.

The Block

11. The blocks used were all about 1-in. square and 6-in. long. All block surfaces, against which the specimens were tested, were prepared in the same way on a surface grinder, Fig. 4. The grinding wheel was "dressed" before each finishing cut was taken and the rate of feed and depth of cut was kept constant. The complete apparatus all assembled and ready for operation is shown in Fig. 5.

PROCEDURE

12. The block holder is clamped in the shaper vise and adjusted so that a dial gage, fastened to the shaper head and run against the holder, indicates that it is level to within one half thousandth of an in. (This is merely a routine check and adjustments are practically never necessary.) The test block is now fas-

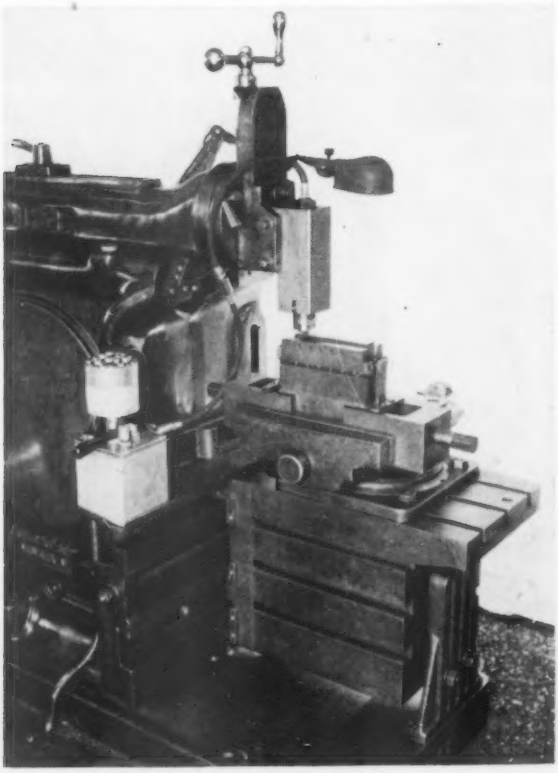


FIG. 5—PHOTOGRAPH OF COMPLETE TESTING APPARATUS.

tened into position and again checked with the dial, and adjusted until it is level to within one half thousandth of an in. Next the specimen is centered in the piston, with the aid of a centering gage, and made level to the block surface. (When flat specimens were used the specimen surface was next polished by running it on emery paper held flat against the block surface.)

13. The machine is set to give a 5-in. stroke and 37 strokes per min. Oil is spread on the surface of the block and the specimen surface is placed in contact with the block under zero load. After 20 strokes the load is increased to 30 lb. Five strokes are run at this load and the machine is then stopped. The excess oil is wiped from the block and specimen and the surfaces polished with a clean dry cloth so that only the boundary film of lubrication remains. Then the test is again started with a 30 lb. load between the surfaces and run for 15 strokes before the load is again increased. In our earlier tests the load was thereafter increased by 30 lb. every 20 strokes. However, it seemed that greater accuracy would be obtained if the load was increased by smaller increments at more frequent intervals; hence, in our later tests the load was thereafter increased by 2.6 lbs. every 5 strokes. With each increase in load the deflection is read on the dial, thus giving us a measure of the frictional resistance for each load. The test is continued until seizure occurs.

14. After a specimen has been run, the surface of contact appears as a well defined area which we can photograph, enlarge, and measure with a planimeter. The recorded load at seizure, divided by the measured area of contact, then gives the pressure between the tested surfaces in lb. per sq. in. at seizure.

DISCUSSION OF RESULTS

15. Early tests, which were run with flat specimens, were of a purely experimental nature and no attempt was made to rate materials on the basis of these results. However, some of the observations made in these early tests are quite interesting and serve to throw more light on the validity of correlating seizure resistance with pressure at the seizure point.

16. When tests were run using flat surfaced specimens the results showed little correlation between seizure resistance and total load. However, Bowden and Tabor[3] had demonstrated, that for flat surfaces in contact, the real area of contact, between the

surfaces, is but a small fraction of the apparent area. For a given pair of surfaces in contact, the real area of contact increased as the load was increased. In another series of tests, Bowden and Tabor showed that when using curved surfaces (or a curved surface on a flat) the apparent and real areas of contact were almost identical in size. Hence, in order to measure the unit pressures at seizure, it is necessary to use curved specimen surfaces, since, only with such surfaces can the area of real contact be known with any degree of certainty. In the tests conducted at the laboratory, the ranges of the total load at seizure for the curved specimens were the same as for the flat specimens of the same material. This presumption was in accordance with Bowden and Tabor's[3] observation that in sliding contact, at a given load, a flat surface against a flat makes contact over the same area as a curved surface against a flat.

17. This first phase of work had been primarily due to the interest in developing the test method and technique. Irons selected for the tests were available in the laboratory and had certain definite differences in composition. In the tests, which are reported here, the specimen and block were of the same material in each test. The results for 13 cast irons and one low carbon rolled steel are listed in Table 1. Block I, with specimens 17 and 18, and block J, with specimens 19 and 20, were commercial irons poured in heavy sections and cooled at a relatively slow rate. All the other cast irons were poured from experimental electric furnace melts into blocks 1¼-in. square and 18-in. long.

18. The values listed for unit pressure, total load, and area of contact are averages of 6 or more independent tests.* Mean deviations from the average unit pressure for a given material is 5½ per cent. A large portion of the deviations can be directly attributed to errors in measuring the area of contact and, as will be pointed out later, to the heterogeneous structure of some of the irons. Allowing for such errors, these results indicate that the unit pressure at seizure is essentially constant for a given material. However, the deviations from the average value of the total load for a given material, due to variations in area of contact, is 12½ per cent. This deviation cannot be explained very easily, and are obliged to conclude that at most the connection between seizure resistance and load is an indirect one.

* In the following discussion the term "unit pressure" is used to indicate the pressure, in lb. per sq. in., between the surfaces of contact while the term "total load" refers to the lb. load applied to the top of the specimen.

Table 1

CHEMICAL ANALYSIS OF MATERIALS TESTED AND RESULTS OF TEST

Block and Specimen	*P (Ave.) (lb. per sq. in.)*	*L (Ave.) (lb.)*	*Brinell No.*		*A (Ave.) (sq. in.)*	*Chemical Analysis*							
			Spec.	*Block*		*T.C. %*	*Si. %*	*Mn. %*	*P. %*	*S. %*	*Cr. %*	*Ti. %*	*Ladle Add.*
1, 2—A	12450	114	229	238	0.0092	2.82	1.39	0.75	0.096	0.054	...	0.041	None
3, 4—B	12040	162	207	223	0.0137	3.31	2.10	0.57	0.029	0.059	0.50	....	FeCr
5, 6—C	11560	161	210	226	0.0138	3.20	2.15	1.26	0.029	0.059	...	....	FeMn
7, 8—D	11360	118	207	215	0.0108	3.10	2.09	0.46	0.380	0.080	...	....	None
9, 10—E	11020	123	207	202	0.0109	3.24	1.94	0.61	0.309	0.055	0.09	....	Graphite
13, 14—G	10030	111	207	226	0.0111	3.01	1.94	0.61	0.309	0.055	0.09	....	None
15, 16—H	9870	165	187	197	0.0166	3.20	2.15	0.92	0.029	0.059	...	....	FeMn
17, 18—I	9775	120	223	229	0.0122	3.04	2.12	0.80	0.137	0.103	0.97	....	FeSi, FeCr
19, 20—J	9445	128	192	199	0.0134	3.04	2.28	0.70*	0.190*	0.100*	0.50*	....	FeSi, FeCr
21, 22—K	9395	115	187	199	0.0122	3.28	2.59	0.69	0.255	0.046	0.19	....	Graphite
23, 24—L	9255	119	226	238	0.0118	3.31	2.14	0.46	0.380	0.080	0.52	....	FeCr
25, 26—M	8770	128	183	193	0.0147	3.31	2.10	0.57	0.029	0.059	...	....	None
27, 28—N	8410	141	197	207	0.0162	3.31	2.10	0.57	0.029	0.059	0.19	....	FeCr
29, 30—O	6580	86	119	128	0.0132	0.15*	...	0.30*	0.02*	0.03*	...	....	.....

* Estimated.

LOAD CARRYING CAPACITY

19. The load carrying capacity of a material depends on two apparently independent characteristics, (1) the characteristic seizure pressure of the material and (2) the characteristic of the material which shall be called, for lack of a better term, "pliability." This term means ability of the material to give contact over a large area. This second factor clearly depends on the elastic and plastic properties of the material as well as its wear resistance. Since materials which have poor wear resistance are not used in parts which operate in sliding contact, the pliability of the surface of materials which are usable, will depend largely on their mechanical properties. The seizure resistance for the various materials rated according to their unit pressures at seizure, are illustrated graphically in Fig. 6. In agreement with field experience these experiments show the high seizure resistant qualities of the cast irons over the steel. However, it should be pointed out that these tests

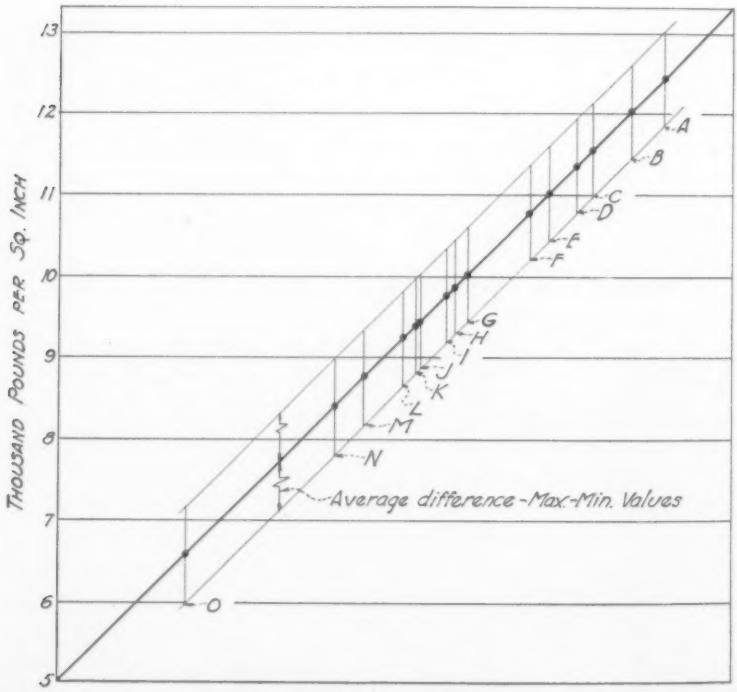


FIG. 6—CHART ILLUSTRATING CHARACTERISTIC SEIZURE PRESSURES FOR 13 CAST IRONS AND ONE LOW CARBON ROLLED STEEL.

are quite limited, showing only one type of steel and only a few of the cast irons. Also, this is a rather arbitrary basis of rating the materials, and all it is hoped to show from these preliminary tests is that there is a definite characteristic unit pressure at seizure which is different for different materials.

DEFORMATION PLASTIC OR ELASTIC?

20. In order to visualize more clearly what is taking place physically when the load between the surfaces is increased and a larger area of contact results, we should know whether the deformation is elastic or plastic. Hertz derived an expression for the contact radius of the circle for a sphere of radius, r, resting on a flat plate under an applied load, W. Assuming that the sphere and plane have the same elastic modulus, E, the radius, a, of the circle of contact is given by the expression:

$$(1.) \quad a = 1.109 \sqrt[3]{\frac{W r}{E}} = K_1 W^{1/3}$$

However, for purely plastic deformation the equation reads:

$$(2.) \quad W = \pi a^2 f$$

where f = maximum pressure before flow. Obtained then, from equation (2):

$$(3.) \quad a = \sqrt{\frac{W}{\pi f}} = K_1 W^{1/2}$$

21. Thus for purely elastic deformation, the area of contact varies as the 2/3 power of the load, while for purely plastic deformation the area of contact varies directly as the load. Experiments[3] indicate that equation (3) more nearly represents the observable facts, although, the results are not as conclusive as one would like them to be.

Table 2

RESULTS FOR SPECIMEN NO. 1 ON BLOCK A

Run No.	*Pressure (lb. per sq. in.)*	*Area of Contact (sq. in.)*	*Load (lb.)*
1	12820	0.0105	134.9
2	12620	0.0078	98.5
3	12600	0.0101	127.1
Av.	12680	0.0095	120.2

22. As mentioned previously, an explanation of the rather large variation in area of contact developed on different runs of the same material (Table 2) cannot be given. These differences in area of contact, in turn, cause large variations in the total load

at failure (since the pressure at seizure is constant). Further along in this study, an explanation for this phenomena is hoped to be found.

23. Microscopic examination revealed, in some cases, wide differences in structure in various parts of the same specimen, or in two specimens from the same iron. This, in fact, explains

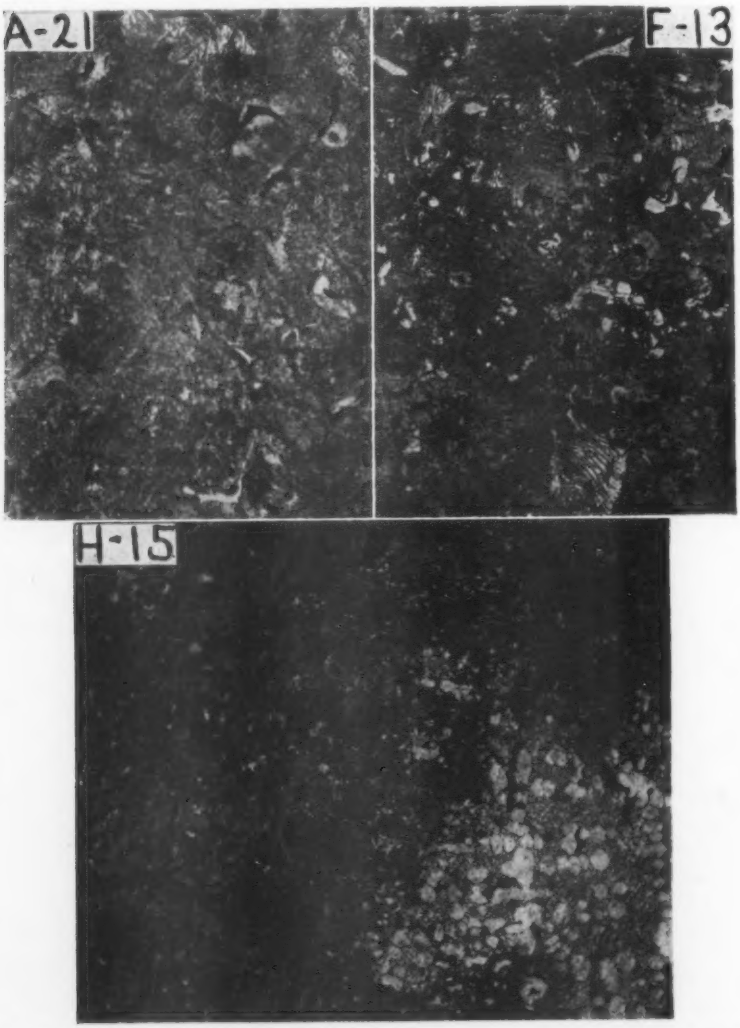


FIG. 7—PHOTOMICROGRAPHS OF THREE SPECIMENS ILLUSTRATING THE VARYING DIFFERENCES IN STRUCTURE. NITAL ETCH. X60.

FIG. 8—MICROGRAPH OF SPECIMEN K-21 SHOWING STRUCTUAL VARIATION. NITAL ETCH. X 200.

why in one or two cases widely different results between two different specimens of the same iron were obtained. This lack of uniformity in microstructure can be observed in Figs. 7 and 8. Clearly, the microstructure of the metal which can effect seizure is that of the surfaces which are actually in contact, and where the structure of the metal is not uniform, the nature of these surfaces can vary. Under such conditions a difference in results of the seizure tests would be expected.

24. Although not yet in position to make a correlation between seizure resistance and microstructure, the experiments to date indicate that large amounts of carbides or ferrite are not desirable. At the same time being unable to find any relationship between Brinell hardness and the tendency of materials to seize, it is unlikely that trouble due to seizure can be avoided by using harder materials.

Bibliography

1. Hardy, W. B., "*Collected Works*," Cambridge University Press, (1936).

2. Jominy, W. E., "*Symposium on Wear of Metals*," A. S. T. M. BULLETIN, (1937).

3. Bowden, F. P. and Tabor, D., PROC. ROY. SOC., 169A 391, (1939).

DISCUSSION

Presiding: H. BORNSTEIN, Deere & Co., Moline, Ill.

A. L. BOEGEHOLD[1]: We think that resistance to scoring is more important in a great many cases than the resistance to wear. I would like to call attention to just one point, and that is the finish on specimens. We have found that by preparing the samples with exactly the same grinding wheel and exactly the same feeds and speeds, we cannot always duplicate the surface conditions, and, consequently, we get differences in the score test results. We have had to resort to the use of the profilometer to be sure that all samples are the same degree of roughness. We have held our samples within the limits of 10 to 15 micro-inches.

DR. C. H. LORIG[2]: Were the blocks and specimens of the same material?

MR. FRIED: Yes, each specimen-block combination was of the same material.

DR. LORIG: Was any attempt made to remove the debris which formed during the operation?

MR. FRIED: Yes. In our tests, some of the materials tested had rather poor resistance to wear and, during the operation, a powder-like material was rubbed from the bearing surfaces and deposited at the ends of the stroke. As the specimen moved inward from these optimum stroke positions, this "wear powder" was wiped away from the section of block surface in contact with the specimen with a clean dry cloth. We feel quite sure that scoring was not due to the wear powder coming between the contacting surfaces.

DR. LORIG: I also agree with Mr. Boegehold that the surface of the specimens under test is a very important factor. We have discarded surface grinding and have gone to lapping to get comparable surfaces for test. By being more careful about surfaces, it has improved the results of our work on seizure.

MR. FRIED: The excellent reproducibility of our results would indicate that in a series of tests run with a given material, the surface finish on the specimen and block was essentially the same in each test of the series. If we had used lapped surfaces in our tests instead of ground surfaces, it is quite doubtful whether our accuracy with regard to reproducibility of results would be significantly improved. However, R. W. Dayton* has found in his tests that the ratings of materials with regard to wear resistance are different when the specimen surfaces are ground finished than when the surfaces are polished, and it is possible that using lapped surfaces in our tests rather than ground surfaces that the ratings of materials as given above will be different.

---

[1] Metallurgist, General Motors Corp., Detroit, Mich.

[2] Metallurgist, Battelle Memorial Institute, Columbus, O.

* METALS AND ALLOYS, vol. 9, December 1939, p. 328.

Coatings for Wood Patterns

By Frank C. Cech* and Vincent J. Sedlon**, Cleveland, Ohio

Abstract

For some years, the matter of pattern coatings has been a question which has been discussed at some length but with little satisfaction. In response to a request, the authors made a survey of the various coatings used in industry, their methods of application, preparation, materials and pigments used, solvents, etc. One questionnaire was sent to a large number of paint and varnish manufacturers and distributors, and another to manufacturers of wood patterns, asking their preference, and reasons for the preference, in coatings. Results of the survey show that (1) three out of four prefer flake to cut shellac, (2) shellac flakes are "cut" by covering with solvent overnight, stirred the next morning and thinned out to proper consistency, (3) grain alcohol is little used as a solvent, (4) patented solvents are replacing wood alcohol rapidly (5) black extract is superseding lampblack as a pigment, (6) vermilion red is a two to one favorite over other shades, (7) yellow pigment is little used, (8) aluminum powder, mixed with shellac or varnish, is gaining favor, (9) oxalic acid should not be used as a clearer for high grade shellac, (10) rubber-set brushes with rubber binding are favored, (11) crockery shellac containers are favored, (12) future pattern coating will probably consist of a shellac priming coat followed with a lacquer top coat, (13) pattern spraying is impractical, (14) a majority of patternmakers prefer A.F.A. standard pattern colors, and (15) pattern purchasers should specify the number of castings to be made from the pattern when ordering it.

Preface

1. In considering certain activities of the Patternmaking Committee of the American Foundrymen's Association, a suggestion was made to the writers that a survey of materials and methods

* Instructor in Patternmaking, Cleveland Trade School.
** Master Pattern Co
Note: This paper was presented at a Patternmaking Session at the 44th A.F.A. Convention, May 7, 1940, Chicago, Ill.

for coating wood patterns would be of interest to many. The writers were invited to make such a survey and report at the 1940 annual meeting.

2. As an apprentice, the writer recalled experimentation in the use of paints and enamels as pattern coatings. Shellac had always been a favorite. Later experimentation produced Duco and it was duly tried on patterns. It failed to penetrate wood and produced a coating that peeled or cracked off and did not wear well.

3. During the World War, shellac was hard to get, and rose to a price that almost prohibited its use for pattern work. Consequently, a varnish was developed that dried fairly well in about 2 hr. It was difficult to sandpaper as it was tacky and accumulated in resinous streaks, much as shellac does when sandpapered before it has had sufficient time to dry thoroughly. Its use was short lived.

4. Then along came lacquer. It has been used with more or less success, but its use on patterns has not been as extensive as will be necessary before passing final judgment on it.

5. The pattern industry is skeptical of using any material but shellac and those concerned are loath to try substitutes.

INTRODUCTION

6. The Pattern Manufacturers of the Associated Industries of Cleveland hold meetings at which time similar problems are discussed. It occurred that interest would be more widespread if their cooperation was secured. The question was brought up at one of their regular meetings; it drew considerable interest and their chairman, V. J. Sedlon, signified his eagerness to cooperate.

7. The paper is consequently presented as a joint undertaking. No claims are made for it. The reader is invited to peruse its contents and pass such comments as he feels will enrich the subject, thereby proving a benefit to the industry as a whole.

OBJECTIVES

8. The objectives of this paper are as follows:

1. To secure such information as can best be given by a *manufacturer* or distributor of shellacs or varnishes that might be used as a pattern coating material.

2. To present results of applying wood pattern coating materials submitted for a trial or test.

3. To secure information pertaining to materials actually used by the *pattern industry* in coating wood patterns under *average* pattern shop conditions.

4. To summarize all information gathered from the questionnaires, make it available to all, including the interested layman having no patternmaking experience.

5. To draw a conclusion that might be used in recommending standards to be used in specifying as well as manufacturing wood patterns.

PROCEDURE

9. Questionnaires were prepared:

a. for the manufacturer and distributor of shellac and varnishes.

b. for the patternmaker or person actually engaged in applying the pattern coatings.

The questions were of a type easily answered but permitting elaboration where necessary.

10. Lists were compiled of patternmakers, foundrymen, and others in the field who might be interested in wood pattern coatings from the registered attendance of A.F.A. conventions. Later additions included A.F.A. chapters and suggested paint and varnish manufacturers throughout the country.

RESULTS OF QUESTIONNAIRES TO MANUFACTURERS OF PATTERN COATINGS

11. Questionnaires were mailed to 78 shellac, paint, varnish, lacquer, and aluminum pigment manufacturers and distributors and individuals who were in a position to contribute reliable information. They represented nine states and ten cities throughout the country. Of the 78 questionnaires sent out, 17, or approximately 20 per cent, were answered.

12. The following are excerpts from letters received as answers to some of the questionnaires:

1. We do not handle pattern coatings.

2. We do not believe we have ever been asked to furnish special products for pattern coatings and believe shellac is almost universally used.

3. We regret we cannot give you any reliable information.

4. We do not manufacture pattern coatings and cannot furnish any data.

5. We do not have any data on pattern coatings.

6. We have never found a creditable substitute for shellac.

7. Any samples of our products you may care to use in your experiment will be gladly furnished.

8. We will be pleased to submit samples for tests at any time.

Many answers to questionnaires were of a type that would overlap those received from industry and consequently are included under that heading.

EXPERIMENTS IN COMPARISON OF VARNISH AND SHELLAC

13. A Cleveland paint company was one of the first to answer and suggest furnishing material for a test. The accompanying photographs show the type of patterns that were designed to test pattern coatings. They represent a deep draw, round and sharp corners, fillets, green sand core, etc., that will help approximate the many demands that sand molding makes on a pattern coating.

FIG. 1.

FIG. 2.

Pattern "A"—Two Coats of Varnish

14. Pattern "A" (Fig. 1), made of sugar pine, was given a priming coat of natural color (yellowish tinge) varnish the consistency of which was that of light machine oil. It was poured directly from the container and no thinner was used. The priming coat felt dry to touch within 25 min. after applying with brush. Grain on the pattern raised slightly. On sandpapering, the coating material was found to be tacky and clogged sandpaper slightly. The end grain of the pattern absorbed the varnish readily.

15. The second coat was applied in natural color and consistency and felt dry to the touch in 2½ hr. It dried with a smooth glossy and tacky coat. The sand stuck slightly to the pattern after 2½ hr. of drying. After fifty sand molds had been made, signs of wear showed on the round corners and the pulpy or soft tissue of the end grain. The brushing quality of the varnish was good.

Pattern "B"—Two Coats of Thinned Varnish

16. Pattern "B" (Fig. 2) was of same material as Pattern "A." However, the priming coat was thinned out with varnish thinner to encourage quicker drying. However, the drying took 45 min. as compared to the previous 25 min. The other characteristics were the same as listed in "A," excepting that the end grain absorbed the varnish very quickly.

17. Application of the second coat was the same as Pattern

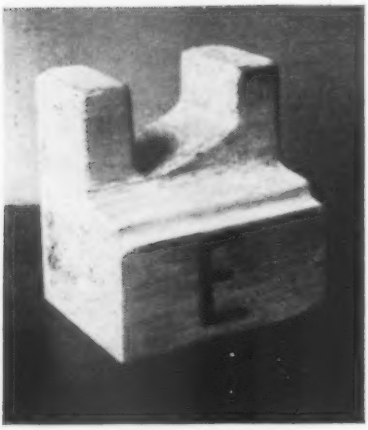


FIG. 3.

"A," excepting the use of the thinned varnish. Results were the same. Sand adhered slightly to the wooden fillets. After 50 sand molds were produced, the only difference observed between "A" and "B" was that "B" had shown more wear (probably once again as much) as "A."

Pattern "E"—Two Coats of Shellac

18. Pattern "E" (Fig. 3) was made of sugar pine. The priming coat was of natural orange shellac. The flakes had been cut to a light consistency at the shop using a patented alcoholic solvent. It felt dry to the touch in 25 min. The grain in the pattern raised. The surface sandpapered readily leaving no resinous deposits. Shellac was absorbed equally well by hard and soft grain, or an excess was left on the soft grain, thus giving an even coating.

19. The second coat was applied of shellac of the same (light) consistency. The surface felt dry to touch in 15 min. with a smooth even coating showing. After 50 sand molds were produced, the pattern had more coating left on it than the previously tested varnish, except on the cope side which had rested on the mold board each time it was rammed. The pattern was first put into the mold for 30 min. after shellacking and showed slight sand adherence in places.

Pattern "F"—Shellac Primer, Varnish Topcoat

20. Pattern "F" (Fig. 4) was made of mahogany. The

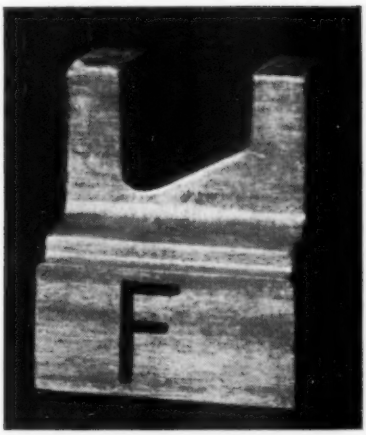


FIG. 4.

priming coat was the same shellac as used on Pattern "E." The surface felt dry to the touch in 15 min. The grain on the pattern raised but the surface sandpapered readily with no resinous deposits left on pattern nor clogging sandpaper.

21. The second coat was with the varnish used on Pattern "A," applied as it came from can. It brushed on evenly and readily, drying to touch in 3 hr. with a smooth but tacky, glossy coat. After use in the production of 50 molds, the pattern coating showed less wear than did the pattern with two coats of shellac.

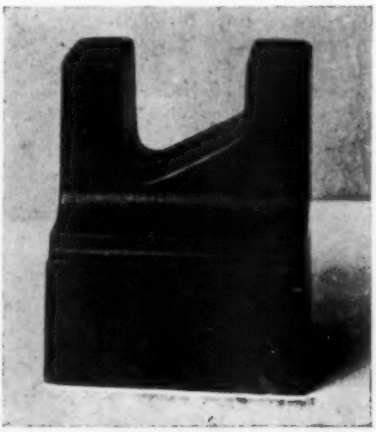


FIG. 5.

Pattern "C"—Red Colored Varnish

22. Pattern "C" (Fig. 5), made of mahogany, was coated with a priming coat of varnish that had been colored red and was of the consistency as it came from the container. The vermilion pigment was first creamed with sufficient varnish to cut it. To this varnish was added later, until the depth of color wanted was reached. It dried to touch in 35 min. and sandpapered readily.

23. The second coat was of the same color and consistency as the first and dried in 55 min. to a high gloss with a smooth but tacky coat. The material was brushed on easily. After 50 sand molds were made, the pattern was in a better state of preservation than any other pattern experimented with so far, showing slight signs of wear.

Pattern "D"—Black Colored Varnish

24. Pattern "D" (Fig. 6) was a mahogany pattern varnished black. The coloring pigment, lampblack, was introduced in the same manner as the vermilion red was in the experiment with Pattern "C." Method of application was also the same. The drying time was one hour for the first coat and 55 min. for the second coat. After a run of 50 molds from the pattern, it revealed little wear.

SUMMARY AND CONCLUSION

25. The experiments with these patterns were inconclusive,

FIG. 6.

if the various means of experimenting are considered. For instance, the color combinations here applied were on mahogany only and not on pine. Would the results have been the same as on mahogany? Only further experimentation would prove this. Also a further experimentation with thinned-out varnish on mahogany might react differently than it did on pine, etc.

26. Returning to the preface in which mention was made of a varnish used during the World War, in a pattern shop that employed on an average of 30 men, the varnish tried here shows much better results than those available at that time. The spreading qualities were above average and the fluidity made an even coating showing no overlap or run. The cost of the varnish is about 15 per cent higher. Whether industry would be willing to pay this additional charge, sacrificing as it must some time in waiting for the varnish to dry, is difficult to answer. It would be well to experiment further with the pattern used in the experiments, or other designed patterns, under more varying circumstances to discover a better coating, if possible.

Results of Questionnaires Directed to the Pattern Industry

27. A second questionnaire was distributed to 273 pattern manufacturers of whom 90, or roughly 34 per cent, answered. This list included jobbing, manufacturing, corporation and foundry pattern shops. The distribution was widespread, including 16 states and Canada and 72 cities throughout the country.

28. In drawing up the questionnaire, it was thought advisable to differentiate between the large, medium and small sized work to allow for a variation in coatings, their treatment or application.

29. After tabulating the returns, the differences found were so slight that all three classes have been combined under the same heading. It may be of interest to note that two-thirds of the questionnaire was devoted to shellac, lacquer taking the remaining third. The questions with their corresponding answers are given in the following paragraphs.

Do You Prefer Shellac, Lacquer, Paint or Enamel?

80 per cent of those who answered are using shellac as a coating.

Reasons given for the use of shellac:

1. **Preserves the pattern.**
2. **Easy application.**

3. Economical.
4. Quick drying.
5. Water proof.
6. Wears well.
7. Does not soften in wet sand.
8. Little build-up on patterns. (Change in dimensions)
9. Can be used as a base for all colors.

11 per cent are using both shellac and lacquer in coating patterns.

Reasons given for using both shellac and lacquer:

1. Shellac is best primer and lacquer is best finish.
2. Lacquer does not dry well on wax fillets, therefore shellac is used as a base.

8 per cent are using lacquer only as a coating.

Reasons given for use of lacquer:

1. Preserves the wood.
2. Wears good.
3. Surface is harder and smoother.
4. Best finish for sand use.
5. More water-proof.

1 per cent use both shellac and enamel as coatings for wood patterns.

No reasons given.

THE FOLLOWING INFORMATION PERTAINS TO SHELLAC

Do You Use Flake, Pulverized or Cut Shellac?

Flake shellac is used by 77 per cent answering.

Cut shellac is used by 23 per cent.

Give Your Preferred Method of Cutting Shellac

It was found that the most popular method of cutting shellac is to cover the flakes with alcohol or other solvent and allow it to stand for 24 hr., during which time it dissolves. Other proportions are about four to one (4 pounds of shellac to one gallon of solvent). This is also known as a "4 lb. cut."

Give Your Preference in Solvents and Reason for This Preference

50 per cent use wood alcohol.

Reasons given for its use:

1. Inexpensive.
2. Satisfactory.
3. Dries fast.
4. Price satisfaction.

36 per cent use other solvents under various trade names.

Reasons given for use of other solvents:

1. Dries a little slower, therefore easier to handle.
2. Dissolves shellac quickly and dries hard.
3. Satisfactory results.

14 per cent use grain alcohol.

Reasons given for using grain alcohol:

1. Cuts faster.
2. Best solvent.
3. Prevents powdering.
4. Has better adhesion.
5. After two or three coats, surface will be absolutely dry.

What Is Your Choice in Black Pigment and Reasons for This Choice?

54 per cent are using black extract.

Reasons given for using black extract:

1. Cleaner to handle.
2. Smoother finish.
3. Richer color.
4. Wears better and has a harder surface.
5. Dissolves better.
6. Dries faster.
7. More heat and water resisting.
8. Dries harder.

FIG. 7—EXAMPLE OF FLAKE SHELLAC USED IN 77 PER CENT OF THE PATTERN SHOPS.

9. Less color needed.
10. Easily mixed with shellac.
11. More economical.

46 per cent are using lampblack.

Reasons given for using lampblack:

1. Seems to harden shellac.
2. Wears better.
3. Economical.
4. Absorbed readily.
5. Patterns do not stick in mold.

What Is Your Choice in Red Pigment and Reasons for This Choice.

38 per cent prefer English vermilion.

Reasons given for this preference:

1. Gives a brighter color.
2. Mixes better.
3. Quality is better.
4. Does not fade.
5. Wears better.
6. Specific gravity less than shellac.
7. Worth the extra cost.
8. Use less for same results.

34 per cent prefer domestic vermilion.

Reasons given for this preference:

1. Satisfactory.
2. Low cost.
3. Specific gravity less than shellac.
4. Dries quickly.
5. Wears well.

28 per cent do not use red or did not answer this question.

What Is Your Choice for Yellow Coloring and Reasons for Same.

19 per cent use yellow pigment.

Reasons given for its use:

1. It gives a nice, deep color.

62 per cent do not use yellow coloring on patterns.

19 per cent use clear shellac for yellow.

Reasons given:

1. Economical.

Do You Use Aluminum Coatings? Reasons If Any.

22 per cent use aluminum coatings.

Reasons given for its use:

1. Looks better.
2. Metallic coverage.
3. Best for production work.
4. Good wearing surface with shellac.
5. Moisture resisting.

78 per cent of those answering do not use any aluminum coatings.

These Are the Most Common Methods for Preparing Powdered Color Pigments.

1. The most popular method is to add enough solvent to pigment to form a paste, mix well and add solvent or shellac to preferred consistency, then strain through cloth while adding to shellac.

2. In the use of black extract, the method preferred is to soak the powder in solvent over night, then stir well, and strain through cloth while adding to shellac.

In both cases, add enough color to the shellac to secure the desired depth of color.

Should the Priming Coat be Clear or Colored Shellac?

47 per cent say it should be colored.

Reasons given:

1. Pigment penetrates the wood.
2. Following coats cover better.
3. Better body for finishing.
4. Colored shellac does not adhere to clear shellac well.
5. Makes it a fast color.
6. Easy to apply the second coat.

41 per cent say it should be clear.

Reasons given:

1. Cleaner sanding operation.
2. Easier and faster.
3. Better adhesion to wood.
4. Does not raise the grain.
5. Better base.
6. Fills the grain.
7. Brighter finish.
8. Harder surface.
9. Better penetration.
10. Easy to check pattern.

12 per cent made no comments.

State the Number of Coats Applied to the Following Types of Wood Patterns:

Temporary Patterns.

82 per cent apply 1 coat only for this type of pattern.

10 per cent apply 2 coats for this type of pattern.

7 per cent do not coat this type of pattern at all.

1 per cent apply 3 coats.

Mediocre Patterns.

74 per cent apply 2 coats for mediocre patterns.

17 per cent apply 3 coats.

6 per cent apply 1 coat.

3 per cent apply 4 coats.

Standard Patterns.

62 per cent apply 3 coats on this type of pattern.

15 per cent apply 2 coats.

10 per cent apply 4 coats.

2 per cent apply 5 coats.

Do You Use Oxalic Acid for Clearing Shellac?

58 per cent *do not* use oxalic acid for clearing shellac.

Reasons for *not* using it:

1. Makes shellac sticky.
2. Takes the life out of shellac.
3. Retards drying.
4. Breaks down body of shellac.
5. No value for appearance.
6. Makes shellac stringy.
7. Shellac loses luster.

42 per cent use oxalic acid.

Reasons given for using it:

1. Better appearance.
2. Clears shellac.
3. Preserves shellac.

State Your Preference, Reasons for and Objectionable Experiences, if any, for Brushes with Tin Binding, Leather Binding and Rubber Binding.

44 per cent use rubber set brushes with rubber binding.

Reasons given for using this type of brush:

1. Does not discolor shellac.
2. Lasts longer.

3. No corrosion.
4. Hair does not come out.

41 per cent use rubber set brushes with tin binding.

Reasons given:

1. Only kind available.
2. Easy to clean.
3. Lasts longer.
4. Bristles do not come out.
5. Easily obtained.
6. Economical.
7. No objectionable features.

12 per cent made no statement.

3 per cent use rubber set brushes with leather binding.

Reasons for using this type of brush:

1. Does not discolor shellac.
2. More satisfactory than tin.

State Your Preference for the Various Containers. (Glass, Crockery, Metal, Enamelware and Wood.)

36 per cent prefer crockery.

Reasons given:

1. Easy to clean.
2. Eliminates discoloration.
3. Preserves colors better.
4. Less evaporation.
5. Preserves shellac better.

30 per cent prefer glass.

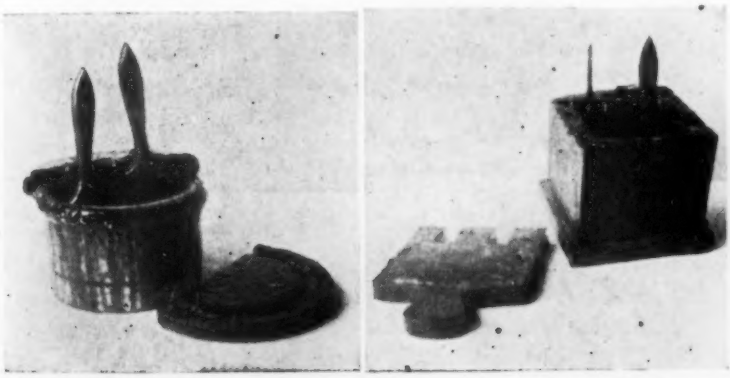


FIG. 8—LEFT—ONE TYPE CROCKERY SHELLAC CONTAINER. FIG 9—RIGHT—WOODEN SHELLAC CONTAINER.

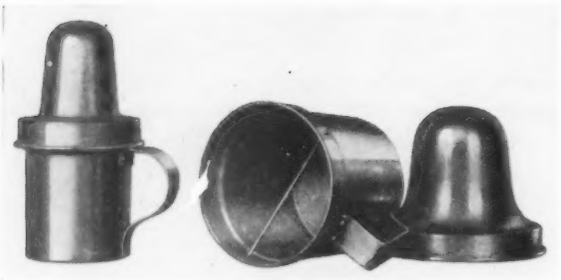


FIG. 10—COATED METAL SHELLAC CONTAINER.

Reasons given:

1. Easy to clean.
2. Does not discolor shellac.
3. Immune to solvents.
4. Economical.

17 per cent prefer metal.

Reasons given:

1. Inexpensive.
2. Not subject to breakage.
3. Durable.
4. Light and easy to handle.

14 per cent prefer wood containers.

Reasons given:

1. Economical.
2. No discoloration.
3. Made in shop.
4. Not easily broken.

3 per cent prefer enamelware containers.

Reasons given for this preference:

1. No breakage.
2. Does not discolor shellac.
3. Easy to clean.

THE FOLLOWING PERTAINS TO THE USE OF LACQUER AS A COATING

Should the Priming Coat be Lacquer or Shellac?

67 per cent of those using lacquer use shellac as a priming coat.

Reasons given for using shellac as a priming coat:

1. Shellac is a better filler.
2. Economical.
3. Good body for lacquer.

4. Lacquer penetrates too freely.
5. Lacquer does not adhere to wax.
6. Lacquer drys better with shellac as a base.
7. Easier to sand shellac.
8. Lacquer dissolves wax.

33 per cent of those using lacquer as a top coat also use it as a priming coat.

Reasons given for its use:

1. Wears better.
2. Better penetration.
3. Does not raise the grain.
4. Penetration of color into the wood.

Should the Priming Coat be Clear or Colored?

46 per cent of those using lacquer use a clear prime coat.

Reasons given:

1. Easier job.
2. Use less sand paper.
3. Shows up imperfections.

33 per cent of those using lacquer use a colored prime coat.

No reasons given.

21 per cent unanswered.

Do You Brush or Spray Your Lacquer?

All the users of lacquer, in this survey, brush it on.

Objections given to spraying lacquer:

1. Runs.
2. Fumes are objectionable.
3. Spraying booth required by law.
4. Too many color combinations on patterns.
5. Not practical.

Do You Prefer the A. F. A. Color Standard?

63 per cent are in favor of it.

Reasons given for favoring it:

1. Better identification.

20 per cent do not favor it.

Reasons given for not favoring it:

1. Takes too much time.

17 per cent made no comment.

SUMMARY

30. Summarizing the returns of the manufacturers and distributors, and especially the reports of the research and similar departments representing the manufacturers, reveals little experimentation on coatings for wood patterns. There may be several reasons for this. Lack of market appreciation may be one. It might be pointed out that the value of the pattern industry in the vicinity of Cleveland alone represents a total annual expenditure of approximately $2,000,000. What per cent of this total valuation represents the cost of coatings for pattern equipment is difficult to say. However, it must be high enough to warrant experimentation for a new coating. Ignorance of the market for such a coating, lack of specifications or listed requisites of the coating, and a laxity on the part of the user to acquaint the laboratories of the paint and varnish companies with these facts, along with an expression of a desire for a new coating, may also be responsible for the absence of said experimentation.

31. The results of the test performed in connection with this survey has been along practical lines, elementary and incomplete, and it is hoped will be the basis of a future paper. It might be presented at some future time at a patternmaking session of the A.F.A.

Coatings

32. The returns of this survey indicate that shellac is preferred as a pattern coating, ranking as first choice.

33. The second choice is lacquer, with shellac as a priming coat, followed by the use of lacquer entirely as a third choice.

Preparation of Coatings

34. Most pattern manufacturers prefer to handle shellac in flake form and dissolve it in quantities as needed. Only about one out of every four purchase their shellac in liquid form. A popular method of cutting shellac is to place flakes in a container and add enough solvent to cover the flakes, let stand for 24 hr., stir, thin down by adding solvent to desired consistency, and strain through cloth before using.

Solvents

35. Denatured wood alcohol is used as a solvent by one-half of the industry. It seems to meet all the requirements. Other preparations have entered this field and are gaining in popularity. Users of these preparations average around 36 per cent, all receiving satisfactory results. The prohibitive price of grain alcohol has apparently discouraged its use as a solvent for shellac. However, it should not be overlooked, as its value for this purpose is ideal. About 17 per cent of those answering the questionnaire still use grain alcohol.

Black Pigments

36. Familiarity with patterns reveals the necessity of identifying parts by coloring. Pigments of various colors are introduced into the shellac for this purpose. A black extract, known by various trade names, and lampblack share about equal popularity. Advocates of the extract claim a deeper penetration of the color into the wood and a better finish. Lampblack users claim that patterns draw better and have a harder finish.

Red Pigments

37. Red shellac is also used in pattern identification. There are two outstanding pigments in use for this purpose, English vermilion and domestic vermilion. English vermilon is richer in color and stronger in coloring properties but higher in cost. Many manufacturers are using the domestic vermilion with good results. In both cases, the specific gravity is lower than shellac. A lighter pigment stays suspended in solution, a heavier one is deposited and necessitates stirring before application. The choice of the manufacturers is about equally divided.

Yellow Pigments

38. Another color used on patterns is yellow. For this purpose, chrome yellow, coloida-lac and andel yellow pigments are used in the shellac. Clear shellac is often used on the bare wood for this purpose. Both methods are considered practical and develop contrast in colors with red and black. In certain instances, where changes in patterns alter the contours of previously painted patterns, the yellow pigment may be necessary to cover parts which were previously black or red. Clear shellac, being transparent, is not practical in such cases.

Aluminum Coatings

39. On the subject of aluminum coatings, about 22 per cent use aluminum powder in shellac. The survey reveals that, although it has merit, there is also considerable criticism. A statement from two foundrymen deserves mention. They claim better drawing results and a longer wearing surface; others are not entirely satisfied. The latter claims that aluminum wears too fast and that they can see no advantages. Experimentation with aluminum coatings is warranted because of its recent appearance.

Preparation of Powdered Pigments

40. It is necessary to prepare powder pigments before their introduction into shellac as they do not dissolve readily. The most popular method is to add enough solvent to the pigment to form a paste, mix well, thin to consistency desired, and strain through cloth before introducing into the shellac. Black extract powder is soaked for 24 hr. in a solvent, then stirred and strained through a cloth.

Priming Coats

41. The observer of the finished product may not attach much importance to the question of whether the first, or priming coat, was clear shellac or a colored shellac. When the color penetrates the wood, it is naturally easier to cover with the second coat. However, it does take more time to apply the various colors on the first coat. Advocates of each method stress such points as, wear, harder finish, better appearance, better adhesion, etc.

Number of Coats for Various Type Patterns

42. A pattern falls into various classifications, according to the expectancy of its use. A product for one casting does not warrant the cost of a finish that will outlive its use. Conversely, a high productive expectancy from a poorly coated product is absurd. For this information, patterns were divided into three classes as follows:

1. Temporary (or 1 to 3 castings)
2. Mediocre (or 10 castings and occasional reorder)
3. Standard (or production run)

One coat of shellac to fill the pores of the wood and to raise the

grain, sanded down to a smooth finish is the popular procedure on a temporary pattern. Two coats for the mediocre pattern and three coats for the standard pattern. It is generally accepted that the consistency of the shellac should not be thick. Three thin coats are much better than two heavy applications.

Use of Oxalic Acid

43. Subjected to exposure in containers, shellac becomes cloudy and has a dirty appearance. This is often corrected or cleared up by the use of oxalic acid. It is not a good practice because the acid tends to break down the body of shellac, causing considerable trouble, such as retarded drying and sticking to the sand. It is being used sparingly in reclaiming shellac.

Brushes

44. A noticeable discoloration is caused by brushes with a tin binding and for this reason, brushes with a hard rubber binding are preferred for shellac, though many using brushes with tin binding claim no objections and prefer them because they are easy to clean.

Containers

45. Suitable containers are important in preservation of shellac. Glass and crockery are most commonly used. They are easy to clean and immune to attack of solvents and chemical reactions. Metal containers, properly coated to prevent chemical reaction, also are used because they are durable and not subject to breakage, as well as being light in weight. Wooden containers are also practical and economical.

Lacquers

46. Lacquer has gained the favor of many manufacturers as a suitable pattern coating. Eleven per cent of the industry is using this material as a final coat over the shellac primer and seven per cent use lacquer exclusively. Shellac is used as a primer because of its value as a wood filler and its quick drying properties. It is also easier to sand smooth and more economical than lacquer. At points where wax is used, as in fillets, etc., these surfaces must be coated first with shellac because lacquer does not adhere to wax and reacts chemically with it.

47. As a finishing coat, lacquer is claimed to make a harder, and consequently a better wearing surface than shellac. Lacquer is also moisture proof and patterns so coated draw well. It is available in colors, thereby eliminating pigment preparation, and has a fine appearance. The spraying of patterns is not practical because of the color combinations used on patterns, and because spraying fumes are objectionable. The best results are obtained by brushing.

48. The following is cited from a letter received from a manufacturer. It is a definite challenge to further experimentation.

> "We have investigated, as completely as possible, our experiences on the finishing of wooden patterns. We have not found anything better than shellac for this purpose, considering cost, convenience, ease of application, etc., but other systems have been used. For instance, one system calls for a first coat of shellac which, on pine, usually raises the grain of the wood. This is sanded and then a coat of patented gray lacquer that is reduced slightly with a shellac thinner used for brush application is applied. Black, orange tints and reds have been used. One or two coats of lacquer are used, whichever may be sufficient. It has been found that this system gives some advantages but it does not last particularly long in contact with sand. Frankly, we do not believe any other fast drying paint system would be expected to give resistance to the abrasive action of sand particles to any definitely greater degree."

CONCLUSION

49. It is in order to list the users expectation of a wood pattern coating along with a description of a pattern and its function. The following is a definition of a pattern as used in the instruction of classes at Cleveland Trade School, and it is rather flexible and inclusive "a pattern is a full-sized model made of suitable material on which provisions have been made for molding, coring, and machining." The pattern is a tool in the hands of a molder; used to form an impression in a sand mold which is later filled with molten metal. The corebox is a frame into which sand is tamped and the sand form is dumped on a coreplate and baked to withstand handling, action of flowing metal and pressure.

50. The principal wear and tear on pattern equipment is abrasive action of sand rubbing against the sides, a constant exposure to a changing humidity, and the effect it has on wood, such as dry pine, mahogany, cherry, etc. To offset the customary wear and render pattern equipment moisture proof, coatings are applied as revealed in this survey. *To merit consideration, the coating should be wood penetrating, quick drying, an elastic preservative that adheres to wood, is durable and moisture proof.*

51. An experiment could be undertaken by the chemistry or physics department of an engineering college in conjunction with the patternmaking or foundry course of engineering.

INDUSTRY SAYS—

52. Three out of every four still prefer flake to cut shellac. The shellac flakes are "cut" by covering shellac with the solvent, allowing it to soak over night, stirring it in the morning, and thinned out to suit each man's whim, which depends on his past experience and training. The absence of scales in pattern shops to weigh the shellac is probably one of the reasons for not observing a more definite or recommended procedure. Grain alcohol, as a solvent, is now little used. Solvents prepared by paint and varnish companies are rapidly replacing wood alcohol which still enjoys a 50 per cent hold on the market.

53. Lampblack, the old reliable black pigment, is losing ground to black extract, a dye that has a deeper, smoother tone with results at least equally as good as those obtained with lampblack.

54. Vermilion red is a two to one favorite over other shades of red.

55. Yellow pigment is little used by pattern manufacturers.

56. Aluminum powder, mixed into shellac or varnish, is slowly gaining favor.

57. The use of pigments depends on the pattern buyers specifications; lacking these the manufacturer follows his own customary practice.

58. The use of oxalic acid is seldom necessary in a good grade of shellac and yet this shellac, because of its grade, would be little

affected by its addition (that is, it could stand a slight adulteration). The cheap shellac is already so poor in grade that addition of oxalic acid renders it unfit for pattern use.

59. Use rubber set brushes with rubber binding for shellacking.

60. Use crockery shellac containers for best service.

61. The future pattern coating, based on this survey, will probably be a shellac priming coat with a lacquer or varnish topcoat brushed on. The use of a spray at this time is impractical.

62. An A.F.A. color standard for finishing pattern equipment is favored by such a large number of replies to this questionnaire that the question merits a paper on a revision in color standards for the next A.F.A. patternmaking session. The use of a natural (transparent) color shellac or varnish for the body of the pattern which forms the bulk of it, would remove the common objection that workmanship is hard to detect through a color. This would protect the buyer of pattern equipment as well as the conscientious manufacturer who attempts to keep in mind the welfare of the foundryman in the building of pattern equipment.

63. It is the hope of the writers that the purchaser of patterns will give more than cursory attention to specifications in ordering patterns. Ask for prices on *Temporary* pattern, one or no coat of coating; a *Mediocre* pattern with two coats and *Standard* or production pattern with three coats.

64. The least that is hoped for in the way of results of this paper, is closer observation of all concerned in the manufacture or use of pattern coatings and the passing on of related information to the trade at large.

ACKNOWLEDGEMENTS

65. The cooperation by the many concerns and persons in making this paper possible, is deeply appreciated by the writers.

Sand Affects Physical Properties of Gray Iron

By H. W. Dietert* and E. E. Woodliff**, Detroit, Mich.

Abstract

The influence of sand properties on the properties of cast materials has been a subject of discussion for some time. In this paper, the authors have studied the effects of moisture and permeability on the various properties of a gray iron. Such properties as fluidity, transverse strength, deflection, porosity, feeding, chill and microstructure were studied. The authors found that fluidity, feeding, transverse strength, and deflection are reduced with excess moisture in the sand. Fracture is finer, graphite refined, steadite areas reduced in size, ferrite areas increased in size, porosity increased, as did also chill, with excess moisture. Fluidity was reduced, fracture is finer and lighter color, graphite is refined, and size of steadite areas reduced with increased permeability. Pearlite areas are more completely developed in low permeability sands and less completely developed with larger areas of ferrite with high permeability. The authors also found that moisture has a greater influence on the properties of the gray iron than permeability, although the latter exerts a noticeable effect.

1. Those who have cast metals in molding sand undoubtedly have noticed that the sand exerted a strong influence on the manner in which the metal solidifies in the mold.

2. This influence of sand on the cooling of metal in a mold, both in the liquid and solid states, is due to the heat conductivity of the sand in the mold. The heat absorption of molding sands varies greatly for the various grades of sands used in the foundry. It also varies, due to the condition of the sand as prepared for molding; for example, variation in moisture.

* President, Harry W. Dietert Co.

** Sales Engineer, Harry W. Dietert Co.

Note: This paper was presented at a Foundry Sand Research Session of the 44th A.F.A. Convention, May 8, 1940, Chicago, Ill.

Table 1

COMPOSITION OF METAL USED IN TESTS

Element	*Per Cent*
Graphitic Carbon	2.81
Combined Carbon	0.61
Total Carbon	3.42
Silicon	2.08
Manganese	0.79
Sulphur	0.097
Phosphorus	0.45
Carbon Equivalent	4.26

3. In a search to determine the degree to which the sand influenced the physical properties of a cast metal, a series of tests as described in this paper were conducted.

SCOPE

4. The magnitude of variables that may exist in a mold is so great that to consider all of them at one time would cause one to become lost in a mass of data.

5. In the presentation of this study, so that it will be of practical value, only two mold variables will be considered; moisture and permeability of the sand.

6. The physical properties of the cast metal that were considered are: fluidity, strength, deflection, porosity, feeding, chill and microstructure.

7. The type of metal to be used in the investigation received careful study. It was decided to use a cupola gray iron, feeling that this type of metal would readily reflect any influence due to the rate of heat absorption by the molding sand. The metal composition is given in Table 1.

TEST EQUIPMENT

8. The molding sands used in this investigation were tested with sand testing equipment built in accordance with A.F.A. specifications.

9. The test patterns used to form the various test specimens for the physical properties of the metal are described in the following paragraphs.

Fluidity

10. The fluidity of the metal was determined by using the fluidity test pattern built in accordance with A.F.A. specifications. The mold was made in a snap flask and poured without a jacket.

Test Bars

11. The 1.2-in. diameter test bars for the strength and deflection tests were poured in molds in equipment built in accordance with A.S.T.M. specifications, with the exception that a 6-in. diameter pipe was used as a flask to give ample sand around the casting. A photograph of this equipment is shown in Fig. 1. The transverse specimens were broken on 18-in. supports.

Chill Test

12. The chill test pattern equipment consisted of a box in which a chill wedge step pattern, 2¼ in. wide and 5¼ in. long, was mounted. Across the width of the wedge appear steps ⅛-in. wide and stepped 1/32-in. The box was rammed with sand and then stripped leaving a mold with the impression of the stepped wedge chill specimen. A photograph of a broken chill-test casting

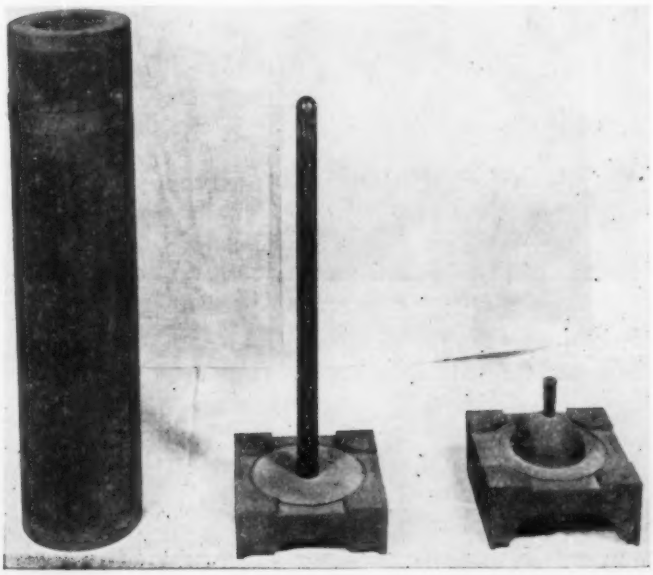


FIG. 1—PATTERN EQUIPMENT USED TO MOLD 1.2-IN DIAMETER TEST BARS FOR DETERMINING STRENGTH AND DEFLECTION.

FIG. 2—VIEW OF A BROKEN CHILL-TEST CASTING.

is shown in Fig. 2. The chill was reported in 32nds of an inch, each step showing white fracture is equal to a chill of 4.

Feeding and Porosity Tests

13. The feeding and porosity of the metal was studied with the aid of a "K" test pattern having a one-in. cross section. Additional metal was fed through the "K" test mold by attaching an additional bob pattern requiring 3-lb. of metal. This additional metal caused the "K" test bar to be more reliable and respond to a change.

Microstructures

14. The micrographs were taken from polished and etched sections of the transverse test bar at fracture and ⅛-in. from the outer edge.

POURING TEST MOLDS

15. Considerable care was exercised in pouring the test molds to eliminate external variables such as cooling of molten metal or change in metal composition for any given series of molds. The molten metal for a given series of molds, for example, those used to determine strength-deflection versus moisture, was poured from a 2-ton mixing ladle into a 500-lb. capacity bull ladle. The bull ladle was transferred 30 ft. to the molds. Two men, each using a preheated 50-lb. capacity hand ladle, poured the molds, thus reducing time to pour any given series of molds to within 3-min.

PRESENTATION OF DATA

16. The data for this investigation is best presented by dividing it into two parts. The first part deals with moisture as the prime variable in the sand, and the second part, with the permeability of the sand as the variable.

Part I — Effect of Moisture in Sand on the Physical Properties of a Gray Iron

17. A group of molds for the various test patterns was rammed using the same sand, but varying the moisture from zero to heavy tempered sand. The zero moisture content mold was obtained by baking the molds in a core oven. The data as presented for this series of tests is data which is representative of a number of repeated tests. The physical properties of the molding sand used are tabulated in Table 1.

18. It may be noted that the green permeability of the sand decreased from 95 to 56 as the moisture content varied from 0 to 7.4 per cent. This reduction in permeability as the moisture increased, reduced the chilling effect of the sand due to the fact that ventilation of the mold was decreased. On the other hand, increasing moisture decidedly increases the chilling effect, the effect being greater in proportion than the opposite effect caused by the decrease in permeability. Therefore, it may be stated that

Table 1

PHYSICAL PROPERTIES OF MOLDING SAND USED IN STUDYING EFFECT OF MOISTURE OF SAND ON PHYSICAL PROPERTIES OF GRAY IRON

Feel	Dried Mold	Dry Side	Temper	Heavy
Moisture, per cent	0	6.2	6.6	7.4
Permeability	95	89.5	68.0	56.0
Green Compression Strength, lb.	..	7.2	6.7	5.6
Deformation, in.	..	0.017	0.019	0.021
Dry Permeability	95	99	95	70
Dry Compression Strength, lb.	76.0	50.0	76.0	90.0
Hardness	..	79	72	68
A.F.A. Specimen Weight, grams	..	165	173	179
Flowability	..	66	66	69
Toughness	..	122	127	118

the effects of moisture would have been greater than those disclosed in this investigation had the permeability been held constant.

19. On the skin of the mold, which is immediately dried on pouring, the dry permeability varies from 95 to 70 as the moisture content changed from temper to heavy temper. If the permeability of the metal-dried skin of the mold is used as a criterion, then the permeability change in this series of tests with moisture as the variable, may be neglected.

Effect of Moisture on "K" Bars

20. An examination of the cross section of the special "K" bars disclosed that the molten metal would feed into a heavy section when the mold was dried, or when the mold was made with a sand whose moisture content was sufficiently low to give a dry feel to the sand, or when moisture was at temper.

21. Note the feeding of "K" bars in left hand of Fig. 3, made in sand with moisture at 0 and 5.1 per cent. The "K" bar made with 7.5 per cent moisture sand does not show any feeding. It does show a gas blow from the high moisture sand. The physical properties such as fluidity, strength, deflection and chill in the metal are tabulated in Table 2 as obtained from molds made with sand of different moisture content.

Table 2

PHYSICAL PROPERTIES OF GRAY IRON AS AFFECTED BY MOISTURE IN SAND

Moisture	0	6.2	6.6	7.4
Transverse Strength, lb	1835	1904	1969	1825
Deflection, in	0.379	0.374	0.368	0.335
Chill in 1/2-in	3.5	6	7	12
Fluidity Buttons	26	26¼	14¼	9
Metal Temperature	2660	2660	2660	2660

Effect of Moisture on Fluidity

22. Through the use of the A.F.A. fluidity test pattern, the effect of moisture in the sand on the fluidity of a metal in a mold was easily obtained. In Fig. 4 is a graphic illustration of the relation between moisture of sand and fluidity of gray iron. The fluidity is little changed by having the moisture at zero or on the dry side of temper, *i. e.*, 0 to 6.2 per cent moisture showed 26 to 26¼ buttons.

23. However, when the sand was tempered at 6.6 per cent moisture, the fluidity dropped to 14¼ buttons. With the sand on the heavy side, having moisture at 7.4 per cent, the fluidity was reduced to 9 buttons, substantially one third of the fluidity for dry sand molds. It may thus be assumed that "misrun" and "cold-shut" casting defects may easily be caused by working sand tempered to the heavy side.

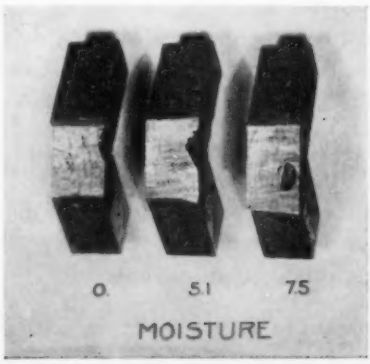


FIG. 3—VIEW OF THREE "K" BARS, CUT TO SHOW THE EFFECT OF MOISTURE IN THE SAND ON FEEDING OF MOLTEN METAL.

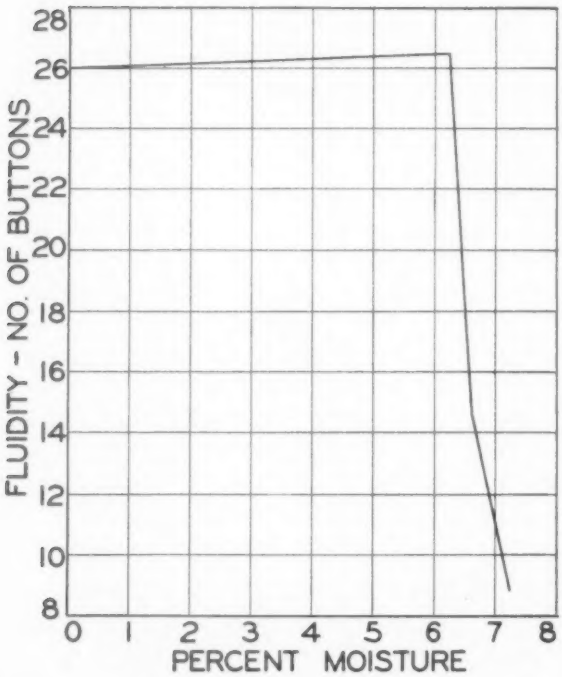


FIG. 4—EFFECT OF SAND TEMPERING MOISTURE UPON IRON FLUIDITY.

Effect of Moisture on Chill

24. Table 2 and Fig. 5 show the relation between moisture of the sand and the chill of gray iron. The moisture-free mold gave a chill of 3½, which was doubled in a mold where the sand was at a good workable moisture content of 6.6 per cent. With moisture increased to 7.4 per cent, the chill increased to 12. This data well illustrates how rapidly the moisture of the sand subtracts heat from the metal after it is poured in a mold.

25. Realizing that the moisture of the sand materially affects the rate of solidification and cooling of a metal in the mold, leads one to believe that the transverse strength and deflection of a metal is vitally influenced by moisture of the sand. This effect may be studied from the data tabulated in Table 2 or from Fig. 6.

Effect of Moisture on Transverse Strength and Deflection

26. The maximum transverse strength was obtained from test bars molded with sand at temper of 6.6 per cent moisture. As

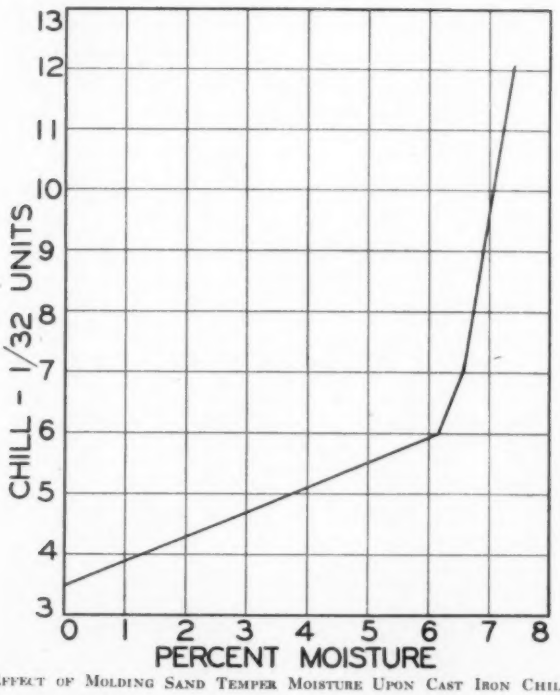


FIG. 5—EFFECT OF MOLDING SAND TEMPER MOISTURE UPON CAST IRON CHILL DEPTH.

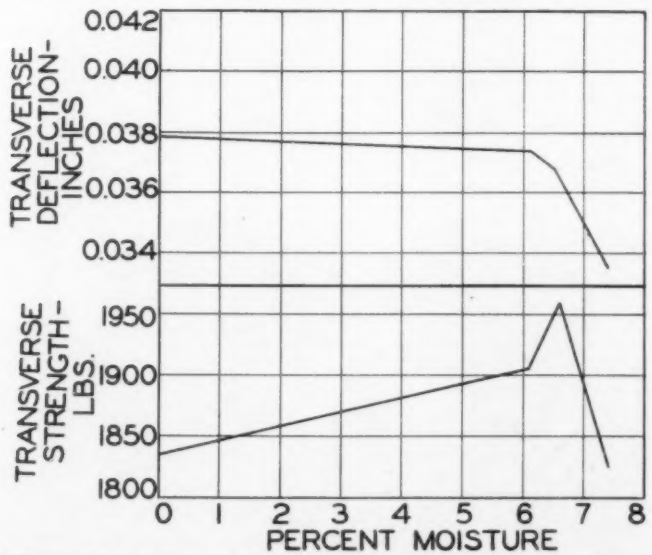


FIG. 6—TRANSVERSE STRENGTH OF GRAY IRON AS AFFECTED BY TEMPER CONDITION OF THE SAND.

moisture content increased from 0 to 6.6 per cent, the strength of the test bars increased from 1835 to 1969 lb., undoubtedly due to a refinement of grain. The strength dropped to 1825 lb. when the moisture of the sand was increased to 7.4 per cent on the heavy side of temper.

27. The above series of test bars were made in a relatively open sand with permeability in the 50 to 90 range. A series of test bars made in a 20 to 30 permeability showed the same characteristics with the exception that peak strengths were usually found in moisture range just ahead of the temper point.

28. Dr. R. Schneidewind, University of Michigan, found that a certain rate of fast cooling caused incomplete pearlite formation with resulting weak ferrite grain. This condition undoubtedly explains in part the low strength of bars cast in high moisture sand where fast cooling is obtained. Another reason for low strength of bars cast in high moisture sand is the small gas-hole inclusions in bars cast in that type sand.

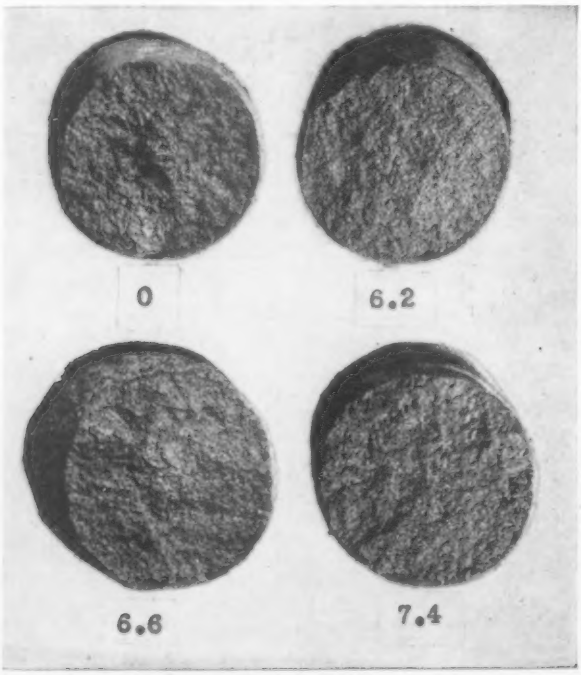


FIG. 7—FRACTURES OF TRANSVERSE TEST BARS MADE IN MOLDS WITH SAND OF MOISTURE CONTENT AS INDICATED BY NUMBERS UNDER EACH FRACTURE.

29. In observing the data for deflection, one may note that the deflection reduced gradually from 0 to 6.2 per cent moisture and then rapidly reduced when moisture was increased from 6.2 to 6.5 and to 7.4 per cent. This shows that the cast metal loses much of its deflection property when cast in heavy tempered sand.

Influence of Moisture on Fracture Appearance

30. The fracture of a series of strength test bars made in molds of different moisture contents, Fig. 7, proves that the moisture in the sand influences the appearance of the metal fracture. The fracture of the bars, made in the dried mold, shows a bluish gray color with a considerable area, in center, of coarser grains. This definitely indicates slow cooling, due to lack of moisture. As the moisture content increases to 7.4 per cent, the fracture becomes lighter in color and has decreasing areas of coarse grains.

GRAPHITIC CARBON VERSUS MOISTURE IN THE SAND

31. A variation of moisture will affect the size of graphitic carbon flakes. For examples, see micrographs in Figs. 8 and 9. The graphite formed in a 1.2-in diameter test bar, poured in a dried mold with zero moisture, is shown at the top in Fig. 8. The graphite is well precipitated, due to comparatively slow cooling. The test bar poured in a mold where the sand was tempered with a minimum moisture of 6.2 per cent, Fig. 8-Bottom, shows longer graphite flakes than that of the dried mold. This is due to the slower cooling of metal in the semi-dry sand mold, since sand tempered on the dry side has a lower permeability than a dried mold.

32. When the test bar is poured in a mold where the sand was correctly tempered to 6.6 per cent moisture, see Fig. 9-Top, the carbon is well dispersed and of shorter flakes than that produced by 6.2 per cent moisture sand. The graphite produced by a mold made with a sand tempered 7.4 per cent moisture and on the wet side, is finely divided showing rapid cooling.

MICRO STRUCTURE VERSUS MOISTURE IN THE SAND

33. The effect of moisture on the pearlite, ferrite, steadite fields and on the manganese sulphide crystals is well illustrated in Figs. 10, 11, 12 and 13.

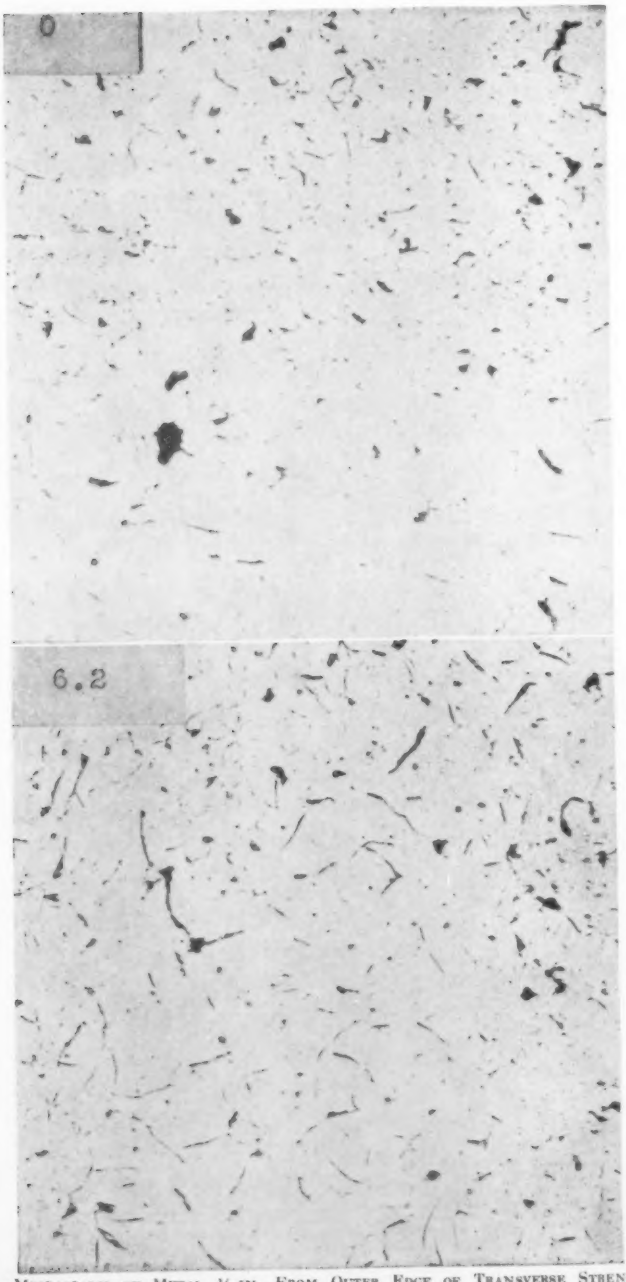


FIG. 8—MICROGRAPH OF METAL ⅛-IN. FROM OUTER EDGE OF TRANSVERSE STRENGTH BAR SHOWING GRAPHITIC CARBON STRUCTURE AS MOISTURE IS VARIED. NUMBERS IN UPPER LEFT HAND CORNERS DESIGNATE PER CENT MOISTURE. MAGNIFICATION: X100.

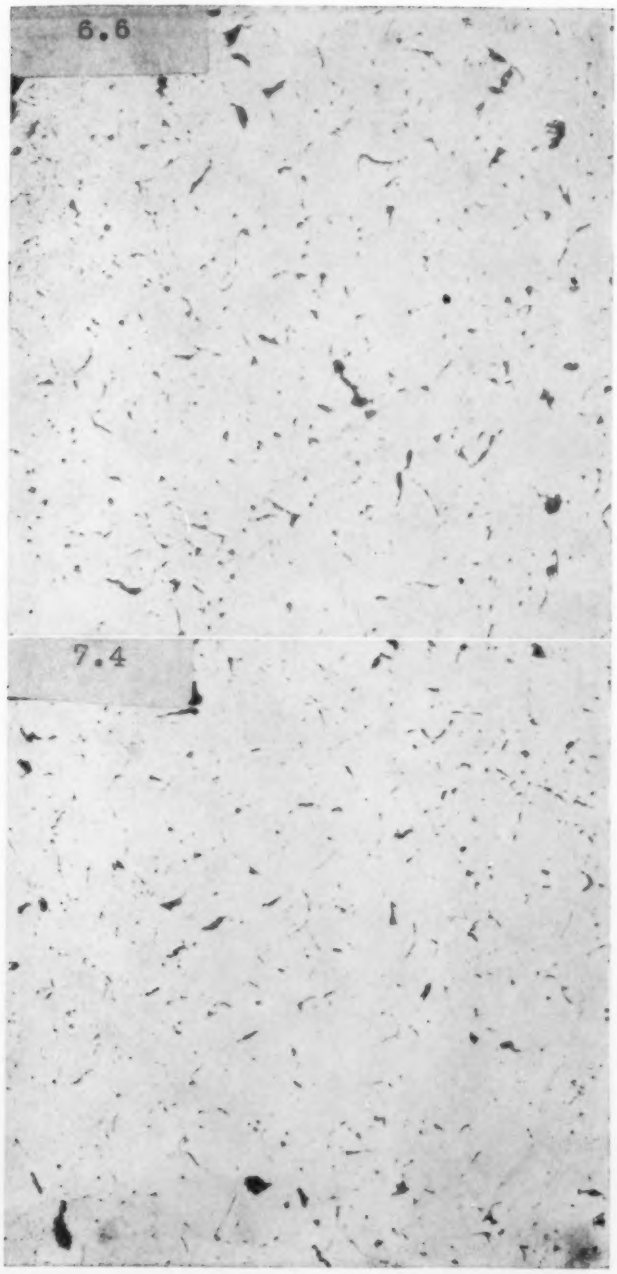


FIG. 9—SAND AS FIG. 8 WITH DIFFERENT SAND MOISTURE CONTENTS.

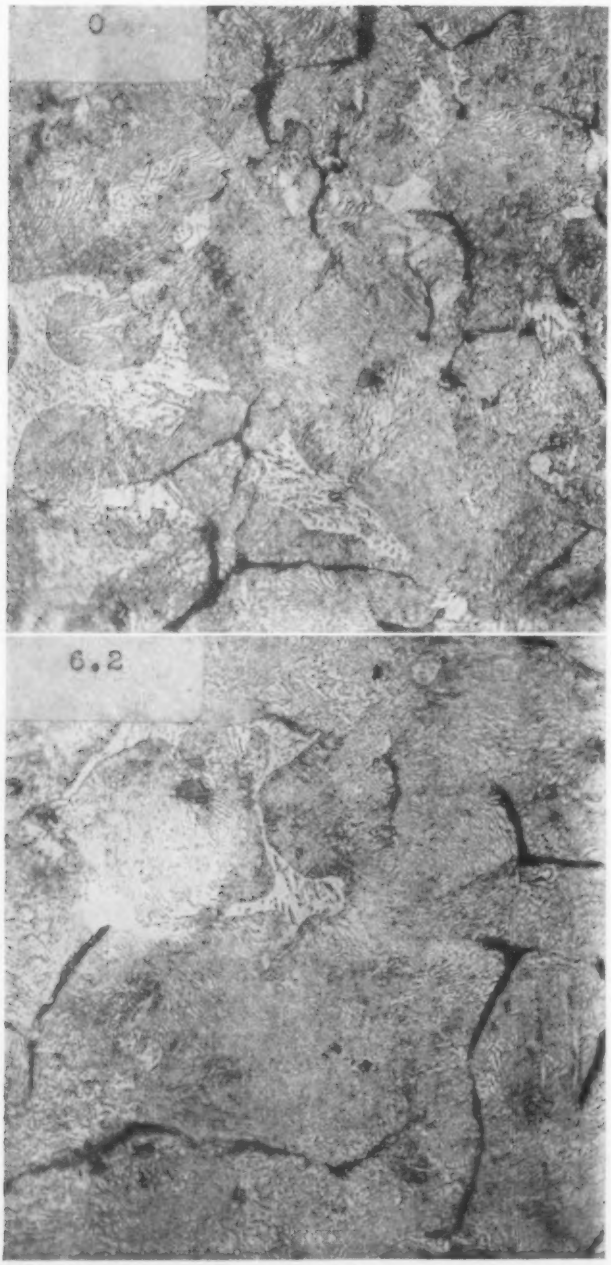


FIG. 10—MICROGRAPH OF A SECTION OF TRANSVERSE STRENGTH TEST BAR, 1/8-IN. FROM OUTER EDGE. NUMBERS APPEARING IN UPPER LEFT HAND CORNERS DESIGNATE MOISTURE CONTENT OF THE SAND. MAGNIFICATION: X500.

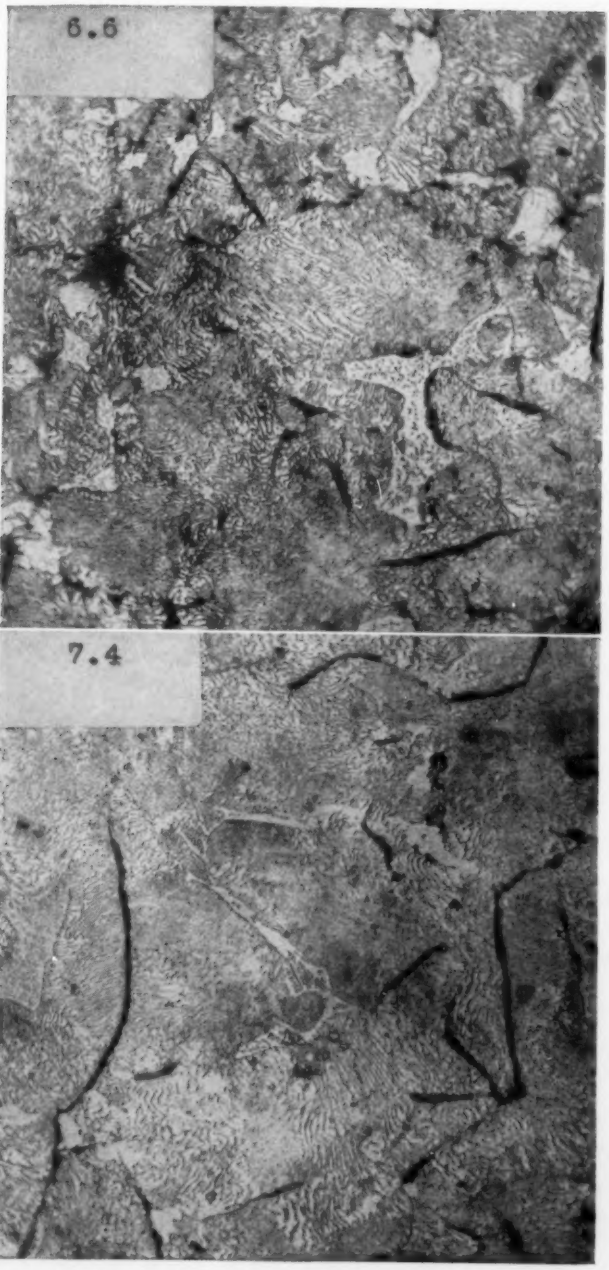


FIG. 11—SAME AS FIG. 10 WITH DIFFERENT MOISTURE CONTENTS.

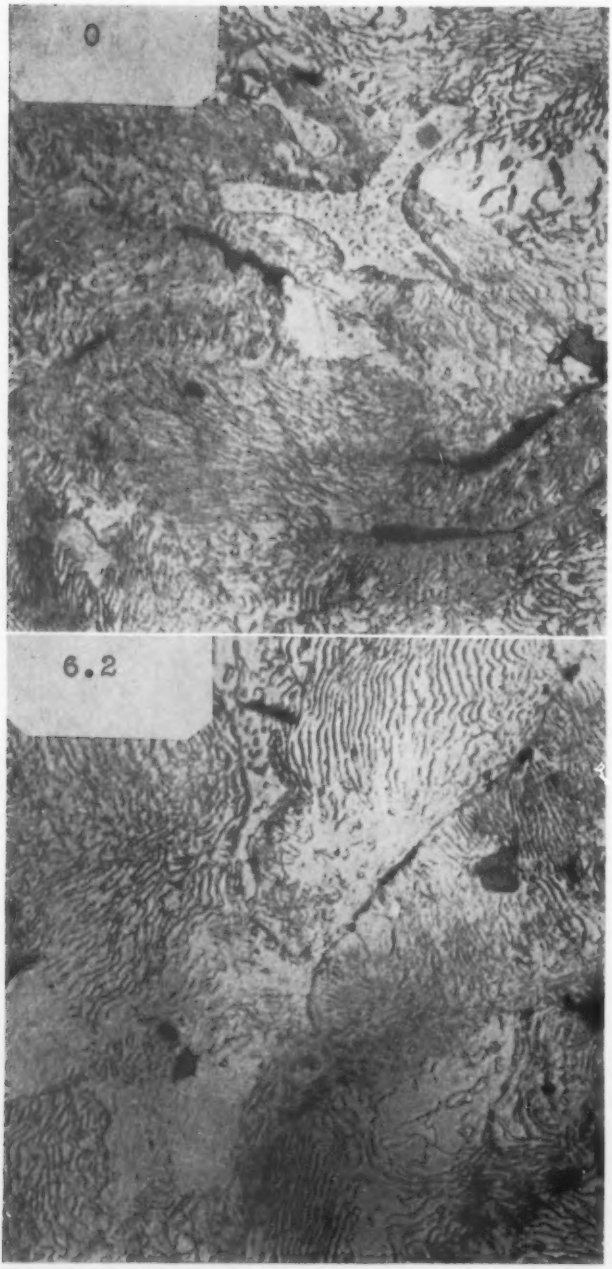


FIG. 12—MICROGRAPH OF METAL ⅛-IN. FROM OUTER EDGE OF TRANSVERSE TEST BAR FOR VARIOUS MOISTURE CONTENTS OF THE SAND, AS SHOWN BY NUMBERS IN UPPER LEFT HAND CORNERS. MAGNIFICATION: X1000.

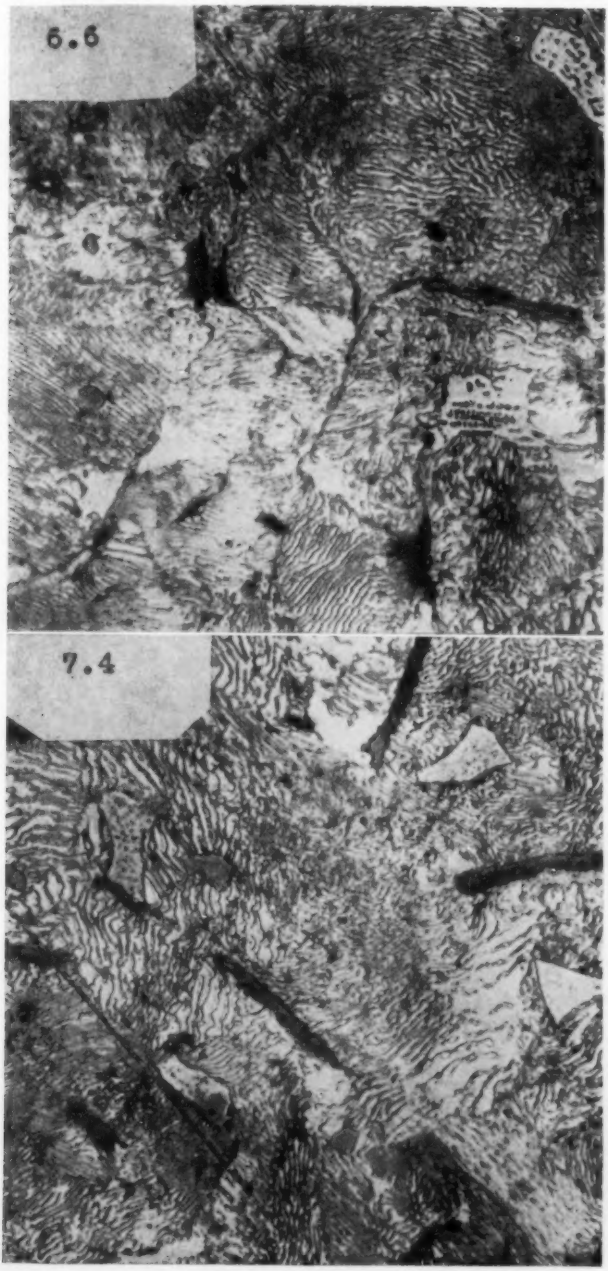


FIG. 13—SAME AS FIG. 12 WITH DIFFERENT MOISTURE CONTENTS.

34. The fields or areas affected the greatest degree are the steadite areas. Where the test bar was poured in the dried mold, or in a mold made with sand on the dry side with 6.2 per cent moisture, the steadite areas are large. As the moisture is increased to the wet side, 7.4 per cent, the steadite areas become smaller since they do not have an opportunity to grow, due to the quick cooling of the metal.

35. The manganese sulphide crystals do not show any appreciable change in size as the moisture content is varied. The pearlitic fields are of a slightly finer structure as the moisture content of the sand increases. The pearlitic field of the test bar made in the dried mold shows a much more open structure than bars made in the green sand molds.

36. The ferrite areas increase in size as the moisture content of the sand increases. This is undoubtedly caused by a more rapid setting of the metal as moisture increases, thus causing pearlite to be incompletely formed. This, the writers feel, caused in part, the low strength obtained in bars cast in high moisture sands.

37. The grain size of the metal shows a marked reduction in size as the moisture content is varied from the dry side to the wet side.

Part 2 — Effect of Permeability on the Physical Properties of a Gray Iron

38. The molds, used in determining the influence of permeability on the physical properties of gray iron, were made of sands ranging from 25 to 170 in permeability. All molds were rammed with sand at temper and then baked in a core oven to eliminate moisture, thus largely dealing with only one variable, namely, permeability. The physical properties of the molding sand are tabulated in Table 3.

39. It was found that the permeability of the sand influenced the rate of metal cooling to such an extent that porosity was minimized with high permeability sand.

Effect of Permeability on "K" Bars

40. The examination of the sectioned "K" bars, as shown in Fig. 14 will reveal that the "K" bar made in 35 permeability sand has a large and deep porous area. The "K" bar cast in 85 per-

Table 3

PHYSICAL PROPERTIES OF MOLDING SAND USED IN STUDYING THE EFFECT OF PERMEABILITY ON THE PHYSICAL PROPERTIES OF GRAY IRON

Moisture, per cent	9.2	6.6	3.6
Permeability	27.3	68	132
Green Compression, lb	7.4	6.7	7.4
Deformation, in	0.022	0.019	0.019
Dry Permeability	35.2	95	159
Dry Compression, lb	73.0	76.0	208
Hardness	65	72	75
A.F.A. Specimen Weight, grams	170	173	170
Flowability	73	66	70
Toughness	162	127	141

meability sand shows a porous area as large but of very shallow depth. The "K" bar cast in the 170 permeability sand shows practically no porous area.

EFFECT OF PERMEABILITY ON PHYSICAL PROPERTIES

41. The data tabulated in Table 4 covers the physical properties of the gray iron, cast in sand ranging from 27 to 132 in permeability. In this series of tests, it was found that the permeability of the same cooled the metal in a mold by convection. The greater the permeability of the sand, the more free the circulation of gases from the face of the mold to the atmosphere. Thus an increased amount of heat would be carried off as permeability is increased. This explains the reduction of porosity of "K" bars in Fig. 14 as permeability is increased.

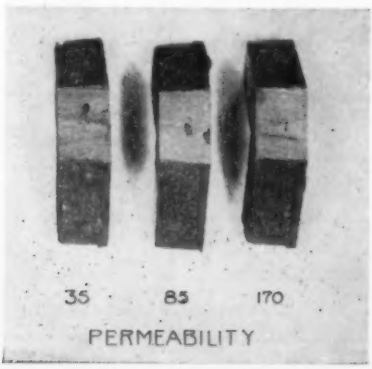


FIG. 14—VIEW OF THREE "K" BARS, CUT TO SHOW THE EFFECT OF PERMEABILITY OF THE SAND ON POROSITY OF CAST METAL.

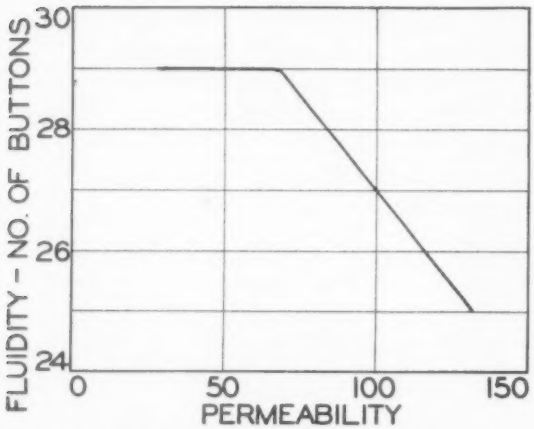


FIG. 15—GRAY IRON FLUIDITY AS AFFECTED BY CHANGE IN MOLDING SAND PERMEABILITY.

Fluidity

42. Should this assumption be true, then an increase in permeability may actually reduce the fluidity of the metal in a mold, providing mold gas pressure is equal. The fluidity data, Table 4 and chart Fig. 15, indicate that the fluidity may be reduced when permeability of the sand is much in excess of that required. At 132 permeability, the A.F.A. fluidity test pattern shows a fluidity of 25, against a fluidity of 29 at 27 to 68 permeability.

Chill Tests

43. Another good check on how permeability cools a metal, is obtained from the chill test. (See data in Table 4 and Fig. 16.) The chill was increased from 9/32 to 11/32-in. as the permeability was increased from 27.3 to 132. This difference in chill is not as

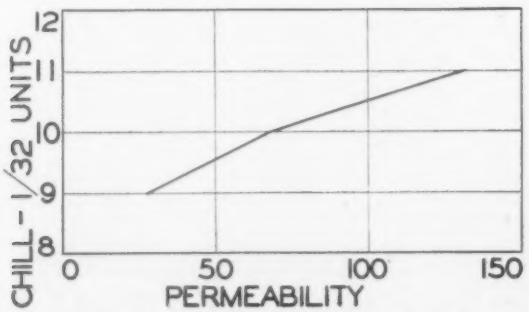


FIG. 16—EFFECT OF MOLDING SAND PERMEABILITY UPON GRAY IRON CHILL DEPTH.

Table 4

PHYSICAL PROPERTIES OF GRAY IRON AS AFFECTED BY PERMEABILITY OF THE MOLDING SAND

Permeability	27.3	68	132
Moisture, per cent	0	0	0
Transverse Strength, lb.	2148	2020	1978
Deflection, in	0.414	0.364	0.350
Chill in $\frac{1}{32}$-in	9	10	11
Fluidity Buttons	29	29	25
Metal Temperatures	2637	2637	2637

great as was experienced with a change in moisture. Thus, it may be assumed that moisture affects the cooling rate of a metal more than a change in permeability.

Transverse Strength and Deflection

44. This study may be continued by observing the effect that permeability has on the strength and deflection of gray iron. (See Table 4 and Fig. 17.) The strength of the metal decreased from 2148 to 1978 lb. as the permeability increased from 27.3 to 132; while deflection decreased from 0.414 to 0.350 in.

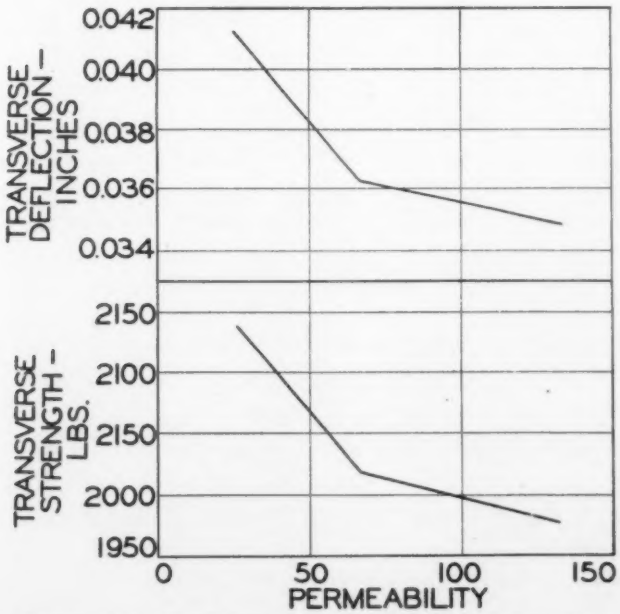


Fig. 17—MOLDING SAND PERMEABILITY AS IT AFFECTS THE TRANSVERSE STRENGTH AND DEFLECTION OF GRAY IRON.

FIG. 18—FRACTURE OF TRANSVERSE STRENGTH TEST BARS, CAST IN SAND WITH 27.3, 68 AND 132 PERMEABILITY.

45. The deflection decrease is readily understood as caused by a more rapid cooling of the metal as the permeability is increased. The explanation of the weakening of the metal as permeability is increased may be assigned to the under cooling phenomena. Slow cooling, as obtained by low permeability, allows sufficient time for the pearlitic structure to form completely, resulting in a strong gray iron. In fast cooling, as obtained with 132 permeability sand, the pearlite does not have sufficient time to form completely, resulting in large weak ferrite areas. A study of the micrographs, as shown in the succeeding paragraph, substantiates this theory.

46. It is interesting to observe the fracture of strength test bars, Fig. 18, noting the bluish gray fracture for the bar cast in 27.3 permeability sand. When permeability is increased to 68, the fracture becomes much lighter in color. The fracture of the bar cast in 132 permeability sand is very light and of fine grain.

GRAPHITIC CARBON VERSUS PERMEABILITY OF THE SAND

47. The rate at which a casting cools is affected by the permeability of the sand in that heat is carried from the metal by gas-flow from the face of the mold to atmosphere.

48. The magnitude of this cooling effect is well demonstrated by the micrographs, Figs. 19 and 20 showing the graphite flakes in test bars poured in sand with permeabilities of 27.3, 68 and 132. The graphite flakes in the metal poured in the 27.3 and 68 permeability sands are coarser than that of the metal poured in a sand of 132 permeability. A comparison between the graphite of

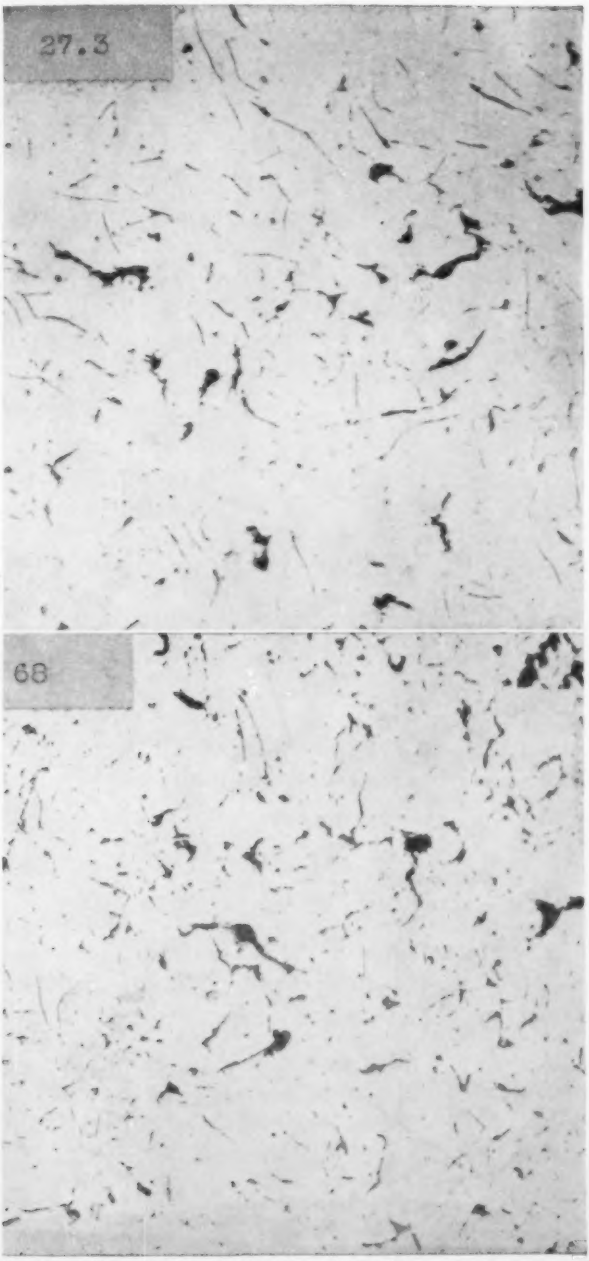


FIG. 19—MICROGRAPHS OF METAL ⅛-IN. FROM OUTER EDGE OF TRANSVERSE TEST BAR, SHOWING THE EFFECT OF PERMEABILITY OF THE SAND ON THE GRAPHITIC STRUCTURE. PERMEABILITY VALUES ARE SHOWN IN UPPER LEFT HAND CORNERS OF MICROGRAPHS. MAGNIFICATION: X100.

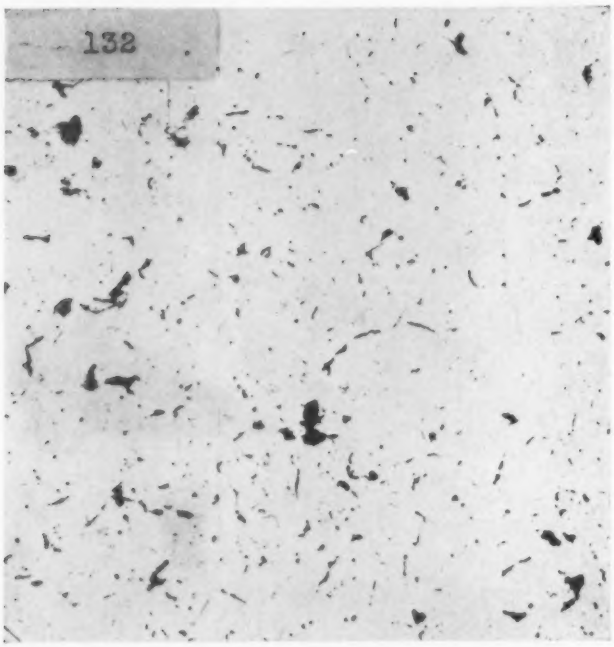


FIG. 20—SAME AS FIG. 19.

bars made in 27.3 and 68 permeability, Fig. 19, shows that the 27.3 permeability sand produces practically all coarse graphite flakes while the 68 permeability sand produced both the coarse and very fine graphite.

MICROSTRUCTURE AS AFFECTED BY PERMEABILITY

49. The permeability of the sand affects the rate of cooling sufficiently to show a distinct change in the pearlite, ferrite and steadite fields and in grain size.

50. A study of micrographs in Figs. 21, 22, 23 and 24 will reveal that the steadite areas are reduced considerably as the permeability of the sand is increased from 27.3 to 132 due to an increase in the cooling rate of the metal.

51. Ferrite areas of appreciable size are produced by the fairly rapid cooling of the 132 permeability sand, which prevents complete formation of the pearlite. This is possibly a good explanation for the decrease in strength of the test bars as the moisture

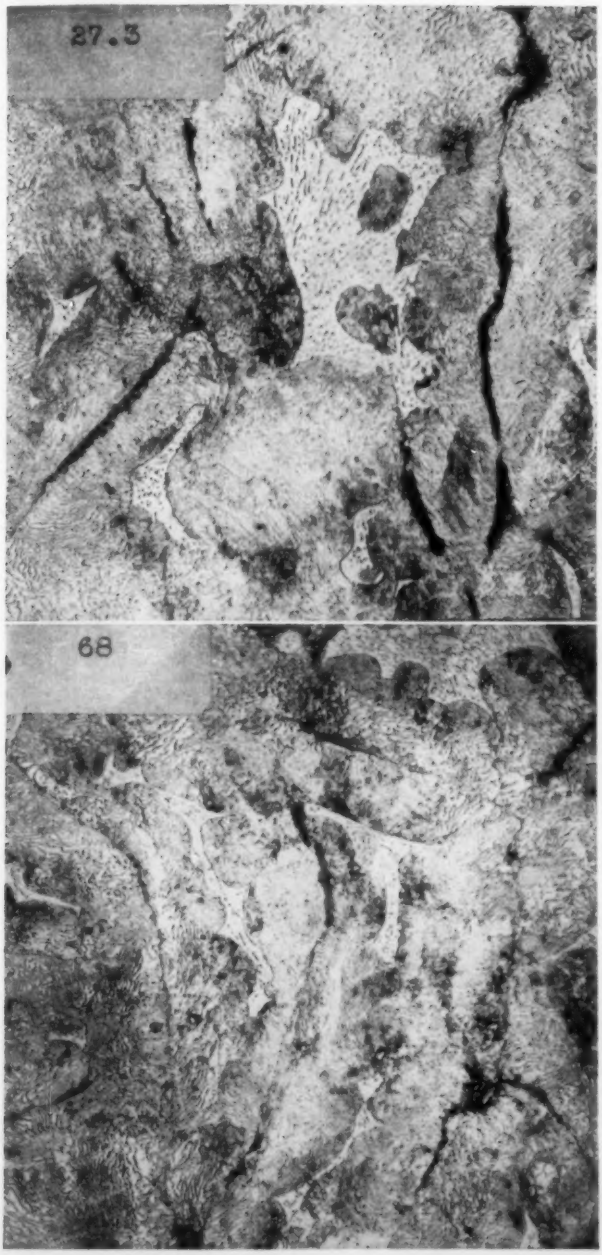


Fig. 21—MICROGRAPHS OF METAL ½-IN. FROM OUTER EDGE OF TRANSVERSE TEST BAR. CAST IN SAND POSSESSING PERMEABILITIES AS INDICATED IN UPPER LEFT HAND CORNERS. MAGNIFICATION: X500.

increased. Probably the greatest change in the metal may be noted in the grain size. For example, the grain size of the metal poured in 132 permeability sand is very small while the grain size of the metal poured in sand with 27.3 permeability is very much coarser. The micrographs in Figs. 21, 22, 23 and 24 illustrate admirably the refinement of grain and graphite as permeability of the sand increases.

CONCLUSIONS

52. The writers appreciate the fact that there are other variables than moisture and permeability of the sand in a mold that affect the rate at which a metal cools in a mold. However, they do believe that the moisture and permeability are two very important properties of a sand that materially affect the physical properties of a cast metal. The data for fluidity, chill and grain size as presented herein, may be applied to practically all cast metals.

53. The findings concerning strength and deflection or ductility may be applied in principle when one knows the effect of rapid cooling on his particular metal. Without question, the

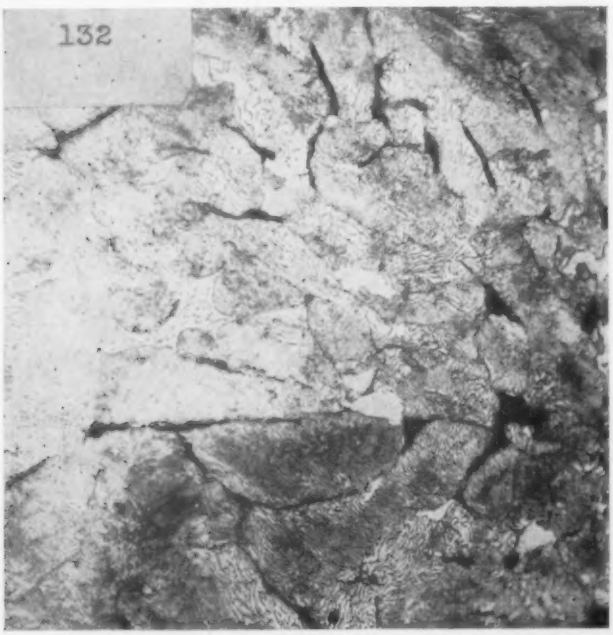


FIG. 22—SAME AS FIG. 21.

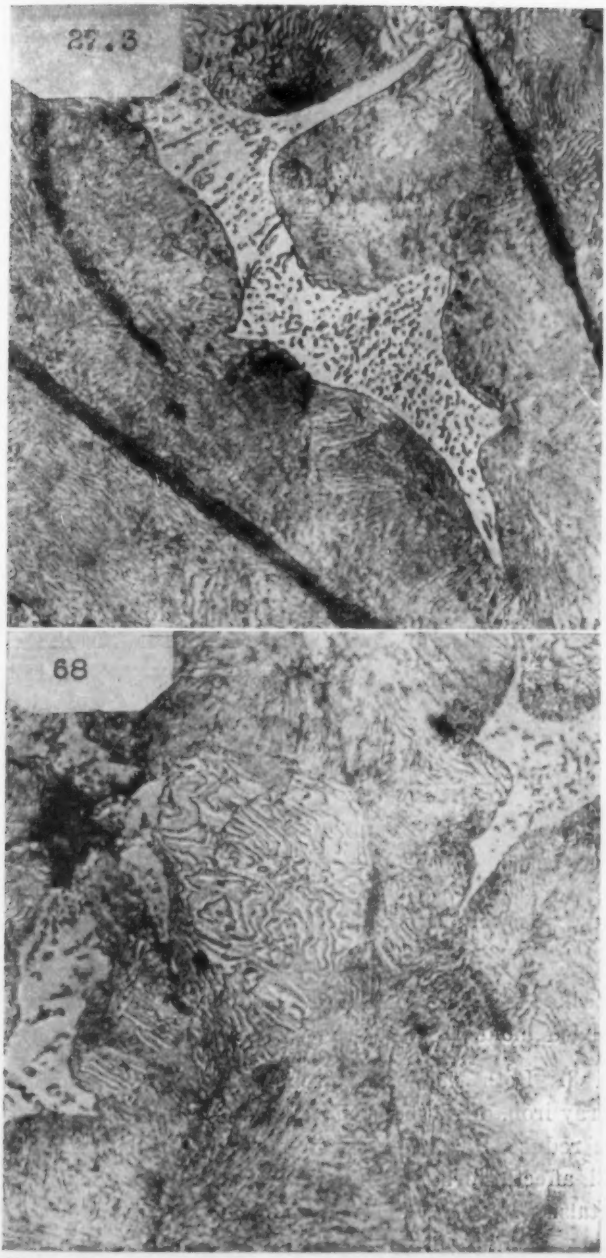


FIG. 23—MICROGRAPHS OF METAL ⅛-IN. FROM OUTER EDGE OF TRANSVERSE TEST BAR. CAST IN PERMEABILITIES AS INDICATED BY NUMBER APPEARING IN UPPER LEFT HAND CORNERS. MAGNIFICATION: X1000.

FIG. 24—SAME AS FIG. 23.

strength and deflection trends may be reversed for certain irons of different compositions other than that used in this investigation. The results of this investigation may be summarized by the following statements.

1. Moisture in a sand when at or above temper will reduce the fluidity of a metal.

2. The feeding of a metal may be greatly retarded by excessive moisture in a sand. Maximum feeding is secured in a dried mold.

3. Both the transverse strength and the deflection of a gray iron, of similar composition as used in this investigation, are reduced by an excess in moisture of the sand. Moisture will affect the strength and deflection or ductility of many metals.

4. The fracture of a gray iron becomes finer in structure and lighter in color as the moisture increases.

5. The graphitic carbon is refined by an increase of moisture in a sand.

6. The steadite grain is reduced materially in size by an increase in the rate of cooling as secured with an increase of moisture in the sand.

7. The ferrite areas for gray iron of composition used, increased in size when moisture was high in the sand, causing a decrease in strength of the metal.

8. High moisture content of the sand also tends to lower the strength due to gas inclusions of small size found in test bars cast in heavy tempered sands.

9. Moisture of the sand has a very great influence on the physical properties of a casting.

10. The porosity of a casting may be minimized by increasing the permeability of a sand providing the mass of metal is not too great.

11. The fluidity of a cast metal may be reduced by using a sand with excess permeability.

12. The chill of a gray iron is increased with an increase of moisture in the sand.

13. The fracture of a gray iron becomes finer and lighter in color as the permeability increases.

14. The graphitic carbon is refined considerably as the permeability of the sand is increased.

15. The areas of steadite are reduced in size by an increase of permeability of the sand.

16. The pearlitic areas are more completely developed for low permeability sands.

17. The pearlite areas are incompletely developed with increased areas of ferrite when permeability is high for a particular section of metal.

18. The permeability of a sand will exert a noticeable influence on all physical properties of a casting.

19. Considering a practical range of moisture and permeability for a casting, it may be stated that moisture in the sand has greater influence on the physical properties of a casting than permeability.

DISCUSSION

Presiding: W. G. REICHERT, American Brake Shoe & Foundry Co., Mahwah, N. J.

N. G. DUNBECK[1]: In this paper Mr. Dietert has shown that the sand is at proper temper with 6.6 per cent water so it is probably a natural sand. He has shown he had certain detrimental results when the moisture content was over 7.4 per cent. I wonder what the result would be if a synthetic sand that is properly tempered at 3.5 per cent water were run at 4.5 per cent.

Are we concerned with the total amount of water in the sand or the amount that the sand is over-tempered?

MR. DIETERT: The sand used in this work is largely natural sand. We did very little work with synthetic sands, but we are led to believe that the results with it would have been the same. For example, at 3 per cent, we would have our maximum strength and at 4 per cent we would have had a material reduction in strength and deflection.

H. WOMOCHEL[2] *(Written Discussion):* The authors conclude that variations in moisture content of the sand have certain effects on the properties of the metal. These conclusions are based on the results of transverse tests made on bars cast in sands having a wide range of moisture contents. It would appear more logical to ascribe the differences in breaking loads to the presence of defects or stress raisers in the bars resulting from unsatisfactory molds. Bars cast under uniform and the most favorable conditions frequently show greater variations than those obtained here.

The photomicrographs of Figs. 9 and 11 are of the irons showing the maximum and minimum transverse loads. There is nothing in these structures to indicate that there should be any difference in physical properties.

MR. DIETERT: I would say that Mr. Womochel had a good point there if we had not made a large number of tests and had not taken the average condition prevailing. In other words, we had to show results from one series of molds, but we made a large number of tests. In every case, the results would follow this same general trend, so they are really the average of a large number of molds. If moisture does not affect the physical strength of our metals, I would like to ask why moisture affects the

[1] Vice President, Eastern Clay Products Co., Eifort, O.
[2] Michigan State College, East Lansing, Mich.

appearance of a fracture of an arbitration bar so materially. We expect to make tensile strength tests from these bars in the near future.

H. L. WOMOCHEL: I do not believe it is possible to arrive at any conclusions regarding the strength of metal by averaging the results of a large number of inferior bars. We have been carrying on research work of this kind at Michigan State College for the past two years, and we know that the sand does have some influence on microstructure, but I do not believe that the authors' results are conclusive. Conclusions regarding the properties of a metal cannot be obtained by averaging the results of a number of poor tests.

MR. DIETERT: I would like to know how Mr. Womochel knows that these bars which we made in our plant were inferior test bars.

H. L. WOMOCHEL: One way that we know is that the authors say so in the paper. The authors say that the bars have gas holes in them.

MR. DIETERT: I did say that the bars in the 7.4 per cent moisture mold did show pin-holes. They are there in minute form; there is no doubt about it. Whenever we do use wet sand we have the pinholes, but the other bars were certainly beautiful cast iron.

H. L. WOMOCHEL: Inasmuch as you have those pinholes in your castings, how are you justified in saying there is this sudden dropping off in the properties?

MR. DIETERT: Good foundrymen certainly have a lot of perseverance. They never give up but keep on until they get a good casting. I would say the microstructures do show some rather positive indications that undercooling is present, as Dr. Schneidewind has shown that cast iron may be undercooled. The best proof would be obtained by waiting a year or two and seeing the results of the progress of this work. I know there will be other investigators like Mr. Womochel, and other foundries, who will really go after this subject. In our daily work, we have found there are factors in the mold other than chemical analysis that affect the strength of our castings. We can have the same chemical composition from day to day and the same iron temperature and get variation in cold shoting. We definitely know, comparing our moisture content by different sand systems that, whenever sand shows high moisture content, we get more cold shots. It has been shown that the back castings of boilers, when made in heavy tempered sand, have inferior physical properties as compared to those made in correctly tempered sand. The deflection of castings made in heavy sand is low. Most foundrymen know of some casting that has failed in service, not because the analysis was incorrect, but because the molding sand was not right.

H. F. TAYLOR[3]: In regard to the fluidity of the metal being governed by the depths of chill expressed in $\frac{1}{32}$-in. units, I notice that the length of spiral does not seem to follow any close relation to this factor.

[3] Metallurgical Engineer, Naval Research Laboratories, Washington, D. C.

For instance in Table 2 is shown a very sudden drop in fluidity from 26 to 14 in. for the small change in chill depth from 6/32 to 7/32-in., whereas no marked difference in length of test piece occurred when chill depths varied from 7/64 to 6/32-in. Mr. Dietert inferred that the drop in fluidity bore a direct relationship to chill properties. I wonder if the length of flow might not be influenced by other factors. I am not sure what type of test piece you are using but in tests I have conducted on cast steel using a modified spiral I have found that moisture varying over many times this narrow range had no effect on length of casting. For any given temperature such drastic changes in fluidity were found to be a function of the condition of the metal, *i.e.* the gas or alloy content.

MR. DIETERT: The fluidity test piece which we used was an A.F.A. test pattern of the spiral type. I do not know what direct answer I can give to the question, but if you will compare the fluidity and the chill diagrams in Figs. 4 and 5 you will see that the fluidity is low and the chill is high when the permeability or moisture is high. We assumed that it was heat absorption of the water and ventilation of the sand that caused this increase of chill. It may be something else.

MEMBER: The sand may be responsible for the condition of the casting. Let us go back to a bar with lugs on; the bar is 3-in. thick with projecting lugs. The lug is ½ by ¼-in. Suppose those lugs are to be drilled and we are unable to drill them. The reason some of them cannot be drilled is that the iron flowing over that bar has chilled and dropped into the lug. I have found that if the sand is out of temper, or a little bit on the wet side, the lugs will get hard enough so they will not drill, and if the sand is in temper they will drill. It is definite proof that the sand is doing it. I agree with what Mr. Dietert has said.

Damping Capacity, Endurance, Electrical and Thermal Conductivities of Some Gray Cast Irons

By C. H. Lorig* and V. H. Schnee,* Columbus, Ohio

Abstract

In this paper, the authors record data accumulated during an investigation of the effect of copper on cast irons. They made a series of low, medium and high-carbon cast irons with additions of copper varying from 0 to 3.0 per cent and studied the effect of that element on the properties indicated in the title of the paper. From their results, they determined that copper may benefit damping capacity at working stresses; that, as copper increases up to 3 per cent, there is a slight decrease in the endurance ratio; that it has little, if any, effect on the thermal conductivity within the percentages of copper investigated; and that the effect of copper on the electrical conductivity, again within the percentage additions investigated, was insignificant. For the records, the authors give an appendix to their paper which shows the method for computing percentage damping capacity.

Introduction

1. The engineering properties of gray cast irons are commonly defined in terms of the ordinary static tests. The tensile strength, transverse strength, deflection and hardness, as determined by tests on standard specimens roughly corresponding to the actual casting sections, are usually considered sufficient for design purposes. In the development of new alloy irons, it is desirable to know the effect of additions of the alloying element on the less frequently determined properties of cast iron. The use of copper as an alloying element has, for example, resulted in many inquiries as to its effect on the thermal and electrical conductivities

* Battelle Memorial Institute.

Note: This paper was presented at a Gray Iron Session of the 44th A.F.A. Convention, May 10, 1940, Chicago, Ill.

and the dynamic properties of cast iron. During the course of an extensive investigation of the use of copper in cast iron conducted at Battelle Memorial Institute by several of the large copper producers, attention has been given to the determination of these properties for a few copper alloy cast irons. It is the purpose of this paper to add the results of these tests to the rather meager data which are available in technical literature.

DAMPING CAPACITY OF COPPER CAST IRONS

2. As pointed out in the discussion of damping in the symposium on cast iron[1], it is not so commonly realized that the effective strength of a vibrating part may be made much greater if made with a material of high damping capacity and only fair strength than if made with a much stronger material lower in these properties. MacKenzie[2] gives the damping capacity as the reason why gray cast irons are so successful in bed plates and frames for machines and vibrating machinery of all kinds.

3. Damping capacity has been defined as that property of a material which causes vibrations to die out. The classic example is that of a tuning fork; made of steel, the fork will vibrate for many seconds; made of cast iron, the vibrations will die out quickly; and if made of lead, the fork would vibrate hardly at all. In this series, lead is said to have the highest damping capacity and steel the lowest. The soft irons have high damping capacities and in this respect are far superior to steel. As the strength, hardness, and stiffness of the irons increase, the damping capacity is lowered but even in the high-strength irons it is better than that of steel.

4. An explanation of the high damping capacity of gray cast irons involves a consideration of its elastic properties, its low modulus of elasticity, compared to that of steel, and its metallographic structure. Gray cast iron is not a truly elastic material. The stress-strain diagram, obtained in the tensile or transverse test, is curved from its origin, showing some degree of plastic deformation as stress is first applied. In cyclic loading, its stress-strain diagram, as sketched by Robertson,[3] is shown in Fig. 1.

5. The hysteresis loop represents the amount of energy absorbed during each stress cycle. The energy used to deform the metal is liberated as heat and causes a rise in temperature of the

[1] Superior numbers refer to the bibliography at the end of this paper.

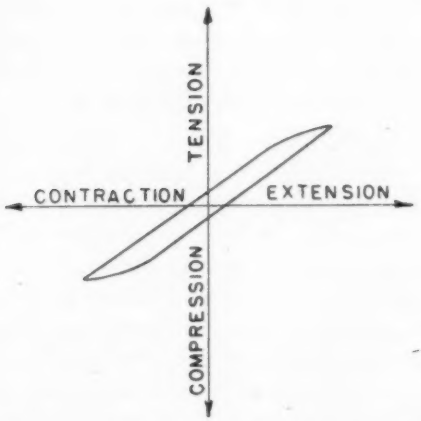


FIG. 1— HYSTERESIS LOOP OF METAL UNDER REVERSED STRESSES.

metal. An unlimited amount of energy can be dissipated without damage by a metal subjected to cycles of stress below its elastic limit. If the material were perfectly elastic between the limits of stress employed, this stress-strain diagram would be a straight line. There would be no hysteresis loop and the damping capacity would be zero. The existence of damping thus implies plastic deformation as the proportional limit of the material is exceeded. The damping capacity varies with the applied stress as well as with the elastic properties of the material. It may be measured as the ratio of plastic strain to elastic strain.

6. The low modulus of elasticity of cast iron relative to steel results in greater deformations in cast iron than in steel for equal stress concentrations. Cast iron behaves as a ductile rather than a brittle material in its ability to deform plastically under low stress. This permits the material to redistribute applied stresses and smooth out stress concentrations that might be serious in steel. It shows its plastic behavior under just the conditions where plasticity is needed to prevent the building up of stress concentrations, that is, at low stresses. Ability to deform locally at low stresses, that is, a low proportional limit, seems to be one of the most important features of "crackless plasticity," the term used by Moore[4] to lump together the combination of properties accompanying low notch sensitivity.

7. The graphite particles present in gray cast iron have no mechanical strength. They act as tiny voids in the material which

conceivably permit plastic deformation of the metal surrounding these voids at lower stress concentrations than would otherwise be the case. This contributes to the damping capacity of cast iron and helps to explain its low notch sensitivity as well.

8. The Wohler Institute, Germany, has been a center of research for the investigation of the damping properties of materials. Foeppl[5] and von Heydekampf[6] have described the different methods that have been developed for the determination of damping capacity. This can be measured experimentally by static tests where the deformation produced by relatively small loads is accurately measured by temperature measurements in a test piece under cyclic loading as in the fatigue test or by the energy absorbed by a fatigue specimen. The free vibration method described by Foeppl, and known in the United States as the Foeppl-Pertz test, has been adopted as somewhat of a standard for the investigation of damping. The apparatus has been described by Smalley[7] and Case.[8]

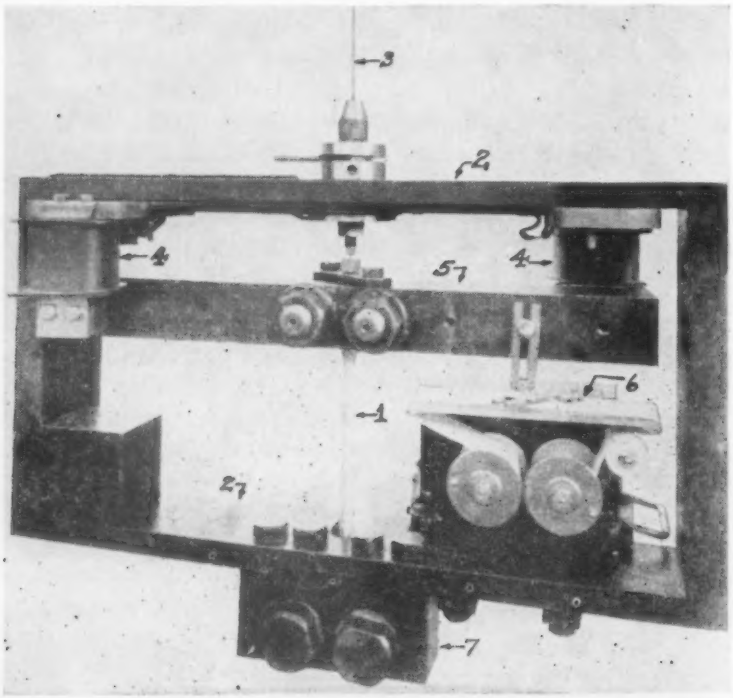


FIG. 2—APPARATUS FOR MEASURING DAMPING CAPACITY. 1—SPECIMEN; 2—FRAME; 3—SUSPENSION; 4—HOLDING MAGNETS; 5—PENDULUM; 6—PEN RECORDER; 7—ANVIL FOR HOLDING SPECIMEN RIGID IN FRAME.

Damping Test Apparatus

9. A photograph of the apparatus used for this work is shown in Fig. 2. The frame is suspended on a flexible wire cable so as to insulate it from any external losses of energy. The vertical test specimen is rigidly clamped at the bottom end into jaws mounted to the base of the frame. The top of the test specimen is clamped by a horizontal bar.

10. The test is started by twisting this bar through the desired angle and holding it in this position by means of two electromagnets located near the ends of the bar. Upon breaking the circuit, a free oscillation of the test bar is set up. A stylus attached to the end of the horizontal bar records a free vibration diagram on a clock-driven chart resting on the lower yoke. The immediate results of this test are diagrams like those shown in Fig. 3.

11. The per cent damping capacity is calculated from the autographic curves. These calculations are tedious and the details of the method are not available in the literature. For convenience, the derivation of the formulas and the method of calculation used have been added as an appendix to this report.

12. An article[13, 14] describes a resonance method of determining damping coefficients recently developed in Germany. It is claimed that this method more nearly simulates the conditions encountered in crankshaft service than the free vibration method. The torsional damping coefficients obtained show that damping is from 80 to 120 per cent greater with cast iron than with crankshaft steels. The damping coefficient, shown by this test, varies with the tensile strength and modulus of elasticity in about the same way as that obtained with other methods of testing.

EXPERIMENTAL DATA

Damping Capacities of Copper Cast Irons

13. Sixteen cast irons were selected for the damping tests. These were taken from a number of experimental heats made in the indirect-arc furnace under carefully controlled conditions. All melts were heated to 2800°F. in the furnace, poured into ladles and held until the temperature had dropped to 2550°F. before casting into test bars. Solid round specimens, of 0.50-in. diameter with an effective length of 7.31-in., were machined from standard 1.2-in. transverse test bars for use in the damping tests. The compositions and static properties of these irons are shown in Table 1.

FIG. 3—TYPICAL AUTOGRAPHIC DAMPING RECORD FOR CAST IRON.

Table 1

COMPOSITION AND MECHANICAL PROPERTIES OF COPPER CAST IRONS USED FOR DAMPING STUDIES

Bar No.	*T.C. %*	*Si. %*	*Cu. %*	*Mn. %*	*P. %*	*S. %*	*Tensile Strength, lb. per sq. in.*	*Transverse Strength, lb.*	*Deflection, in.*	*Hardness, Brinell at half radius*
4	3.37	1.00	0.00	0.52	0.22	0.10	40,500	2850	0.321	205
5	3.36	1.07	1.00	0.52	0.22	0.10	45,500	2900	0.261	221
6	3.32	1.09	1.72	0.52	0.22	0.10	49,000	2950	0.243	245
12	3.36	1.09	2.09	0.54	0.22	0.09	49,000	3850	0.312	259
13	3.39	1.08	3.01	0.54	0.22	0.09	51,500	3450	0.300	244
30	3.16	1.54	0.00	0.57	0.22	0.11	48,500	3250	0.379	213
31	3.20	1.50	0.53	0.57	0.22	0.11	47,500	3350	0.378	218
32	3.18	1.59	0.99	0.58	0.23	0.11	50,000	3250	0.300	228
33	3.15	1.58	1.45	0.58	0.23	0.11	53,000	3300	0.300	233
34	3.18	1.49	1.98	0.58	0.23	0.11	54,500	3600	0.312	242
35	3.16	1.44	3.10	0.58	0.23	0.11	56,000	3550	0.291	253
47	2.90	1.57	0.00	0.57	0.21	0.10	55,500	3500	0.347	225
48	2.89	1.57	1.01	0.57	0.21	0.10	58,500	3500	0.278	246
49	2.87	1.58	1.34	0.57	0.21	0.10	60,000	3600	0.281	253
50	2.91	1.54	1.95	0.56	0.22	0.10	59,500	3400	0.252	261
51	2.96	1.56	3.00	0.56	0.22	0.10	60,000	3750	0.293	266

14. The per cent damping capacity as calculated for different values for the maximum fiber strength are given in Table 2. These data are taken from a single test of each iron, although actually from four to eight tests were made. Tests were begun at low maximum fiber stresses and the stress increased in each test.

15. The average damping capacities for various maximum fiber stresses for each of the runs are summarized in the charts, Figs. 4, 5, and 6. It is evident that at low stresses, the irons differ very little in their damping capacities, but as the maximum fiber stress increases the stronger, alloyed irons are lower in damping capacity than are the weaker irons of the different groups.

16. The damping capacities of the cast irons were computed at maximum fiber stresses equal to 15 and 35 per cent of the tensile strengths of the irons. These values are given in Table 3.

17. This information is probably of greater practical importance than is the information on damping capacities given in the charts. It takes into account that iron castings are stressed in service considerably below the tensile strengths of the irons. At working stresses equal to 15 per cent of the tensile strength, the damping capacities of the irons appear to increase with the alloy content. Somewhere between a working stress of 15 and 35 per cent of the tensile strength, this order in the damping capacities is reversed, the copper irons then becoming of lower damping capacity than the irons without copper. In engineering applica-

Table 2

PER CENT DAMPING CAPACITY OF COPPER CAST IRONS

Bar 4 — Carbon, 3.37% Copper, 0.0%		Bar 5 — Carbon, 3.36% Copper, 1.00%		Bar 6 — Carbon, 3.32% Copper, 1.72%		Bar 12 — Carbon, 3.36% Copper, 2.09%		Bar 13 — Carbon, 3.39% Copper, 3.01%		Bar 30 — Carbon, 3.16% Copper, 0.0%	
Max. Fiber Stress, lb. per sq. in.	Damping Capacity, Per Cent	Max. Fiber Stress, lb. per sq. in.	Damping Capacity, Per Cent	Max. Fiber Stress, lb. per sq. in.	Damping Capacity, Per Cent	Max. Fiber Stress, lb. per sq. in.	Damping Capacity, Per Cent	Max. Fiber Stress, lb. per sq. in.	Damping Capacity, Per Cent	Max. Fiber Stress, lb. per sq. in.	Damping Capacity, Per Cent
16,600	31.0	18,400	29.3	19,200	22.0	22,100	19.0	19,800	23.1	17,600	23.2
12,800	21.0	14,400	18.7	15,600	19.0	18,600	14.8	16,100	18.7	14,700	16.4
10,600	16.5	12,100	17.9	13,300	16.3	16,000	12.3	13,700	17.1	12,400	13.7
8,800	13.7	10,000	14.9	11,200	12.1	13,900	15.1	11,900	12.0	10,600	11.4
7,400	12.8	8,100	13.3	9,200	11.7	12,300	10.7	10,600	12.3	9,000	11.8
6,100	11.0	6,800	9.9	7,700	12.3	11,200	12.8	9,000	12.3	7,700	9.3
5,100	9.8	5,800	11.0	6,400	9.9	9,500	9.7	7,700	10.2	6,600	6.5
4,100	9.1	4,800	7.6	5,300	9.0	8,100	9.7	6,500	10.9	5,600	7.6
3,200	6.7	4,100	10.0	4,300	8.5	6,900	10.4	5,400	9.4	4,900	8.8
2,600	7.0	3,300	7.6	3,600	7.6	5,900	13.3	4,500	9.5	4,200	6.0
1,900	6.1	2,600	7.0	3,000	6.8	4,900	8.7	3,600	7.9	3,600	6.9
		2,000	4.9	2,400	7.9	4,100	9.6	3,100	7.0	3,100	7.0
		1,600	4.8			3,500	8.7	2,600	8.6	2,700	5.3
						2,900	7.5	2,100	7.3	2,200	4.0
						2,500	6.6				
						2,000	6.5				
						1,500	6.5				

Table 2 *(Cont.)*

Bar 31 — Carbon, 3.20% Copper, 0.53%		Bar 32 — Carbon, 3.18% Copper, 0.99%		Bar 33 — Carbon, 3.15% Copper, 1.45%		Bar 54 — Carbon, 3.18% Copper, 1.98%		Bar 35 — Carbon, 3.16% Copper, 3.10%		Bar 47 — Carbon, 2.90% Copper, 0.0%	
Max. Fiber Stress, lb. per sq. in.	*Damping Capacity, Per Cent*	*Max. Fiber Stress, lb. per sq. in.*	*Damping Capacity, Per Cent*	*Max. Fiber Stress, lb. per sq. in.*	*Damping Capacity, Per Cent*	*Max. Fiber Stress, lb. per sq. in.*	*Damping Capacity, Per Cent*	*Max. Fiber Stress, lb. per sq. in.*	*Damping Capacity, Per Cent*	*Max. Fiber Stress, lb. per sq. in.*	*Damping Capacity, Per Cent*
18,200	23.6	20,200	21.4	20,200	23.2	18,900	19.1	21,900	18.6	19,800	19.9
15,100	15.6	16,700	16.7	16,700	18.1	15,800	15.6	18,300	13.6	16,600	17.6
12,900	15.1	14,200	14.7	14,100	14.6	13,700	15.0	16,100	12.1	13,600	12.7
11,200	12.4	12,400	12.4	11,900	13.9	11,900	13.9	14,200	11.8	11,300	10.7
9,800	12.6	10,600	11.1	9,900	11.1	10,300	11.5	12,600	9.9	9,800	8.6
8,600	10.4	9,100	10.0	8,300	10.5	8,800	10.0	11,000	10.1	8,600	7.7
7,300	10.4	7,700	11.7	6,400	9.8	7,600	10.0	9,500	8.7	7,300	7.7
6,400	7.6	6,700	8.4	5,400	8.4	6,600	9.3	8,000	8.6	6,300	5.4
5,800	7.2	5,500	9.4	4,400	7.9	5,700	8.9	6,700	14.4	5,400	6.8
4,700	8.0	4,600	9.0	3,500	7.8	4,700	8.0	5,600	8.2	4,600	5.0
3,900	7.6	3,700	7.4	2,700	6.3	3,800	6.6	4,800	9.6	3,700	5.4
3,400	8.1	3,100	6.0	2,000	6.3	2,900	6.9	3,900	6.4	2,900	4.6
2,700	7.6	2,300	5.9			2,000	5.7	3,400	7.7	2,350	3.6
2,100	5.2							2,300	6.0		

Table 2 *(Cont.)*

Bar 48 — Carbon, 2.89% Copper, 1.01%		Bar 49 — Carbon, 2.87% Copper, 1.34%		Bar 50 — Carbon, 2.91% Copper, 1.95%		Bar 51 — Carbon, 2.91% Copper, 3.00%	
Max. Fiber Stress, lb. per sq. in.	*Damping Capacity, Per Cent*	*Max. Fiber Stress, lb. per sq. in.*	*Damping Capacity, Per Cent*	*Max. Fiber Stress, lb. per sq. in.*	*Damping Capacity, Per Cent*	*Max. Fiber Stress, lb. per sq. in.*	*Damping Capacity, Per Cent*
21,400	14.7	23,700	18.1	22,100	15.7	23,500	17.1
18,400	14.7	18,200	13.5	19,100	11.8	20,300	13.9
15,400	10.0	14,900	9.9	16,200	11.1	17,500	11.5
12,300	9.5	11,900	8.7	13,700	9.3	14,800	10.0
10,100	7.9	9,600	8.4	11,900	8.8	13,100	10.2
8,500	7.5	8,600	6.2	10,200	9.3	11,600	9.0
6,900	6.6	5,100	6.5	8,500	8.3	9,500	8.6
5,300	5.7	4,100	5.7	7,000	7.5	7,000	7.2
4,100	5.4	3,300	4.6	5,800	6.0	4,700	5.7
3,100	4.3	2,600	4.9	4,500	5.1	2,900	5.5
2,700	3.6	1,900	3.9	3,200	4.7	1,800	4.1
		1,500	3.5	2,500	4.2		
				2,000	3.1		

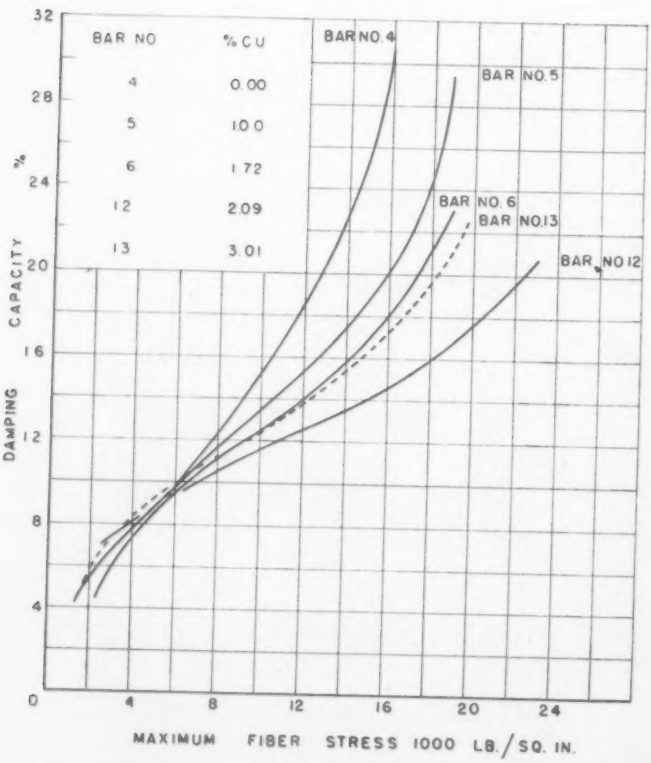


FIG. 4—DAMPING CAPACITIES OF HIGH-CARBON COPPER CAST IRONS.

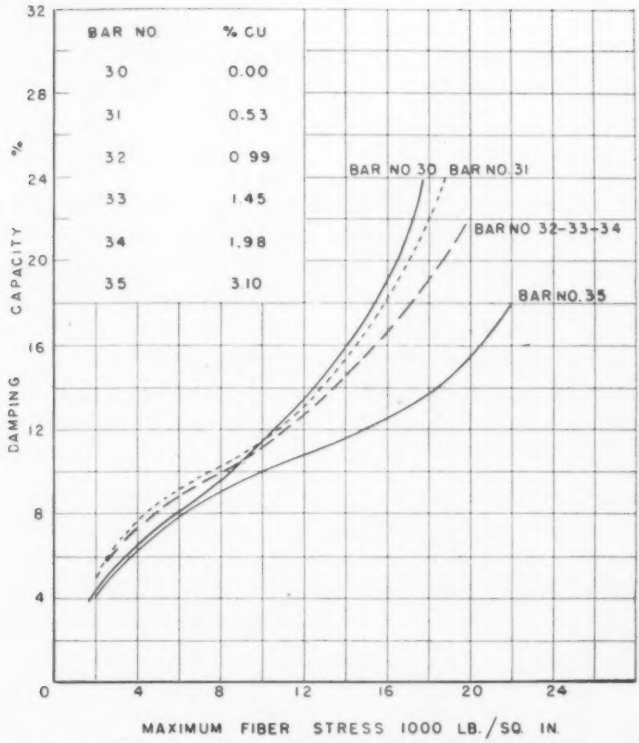


FIG. 5—DAMPING CAPACITIES FOR MEDIUM-CARBON COPPER CAST IRONS.

tions, cast irons are seldom called upon to resist stresses that are above 20 per cent of the tensile strength. It appears probable that the damping capacity at working stresses, computed on the basis of a certain percentage of the tensile strength, may be benefited by strengthening with copper.

ENDURANCE OF COPPER CAST IRONS

18. The endurance limit of a metal is the highest stress which it will bear for an unlimited number of repetitions without fracture. With ferrous materials, in the absence of corrosion, it is found that, if a specimen withstands 5 to 10 million repetitions of a given stress, it will withstand that stress indefinitely.

19. The test is usually made by beam loading a rotating test piece of cylindrical section, so that the stress varies from a maximum in tension to a maximum in compression at each revolution.

The stress reported is the maximum tensile or compressive stress, that is, half the stress range. Almost all endurance data for gray irons have been obtained by the standard rotating beam test. Such testing is fully described by the American Society for Testing Materials.[9]

Endurance Testing

20. The standard test is made on specimens carefully freed from notches by polishing, since steels and non-ferrous alloys are very seriously weakened in fatigue by notches, poor fillets, tool marks or any type of stress raiser that produces local stress concentrations. Gray irons differ from other engineering materials in their immunity to the "notch effect." This has been many times demonstrated, especially by Kommers.[10] As the tensile strength of the iron increases, the iron begins to show a slight effect of the

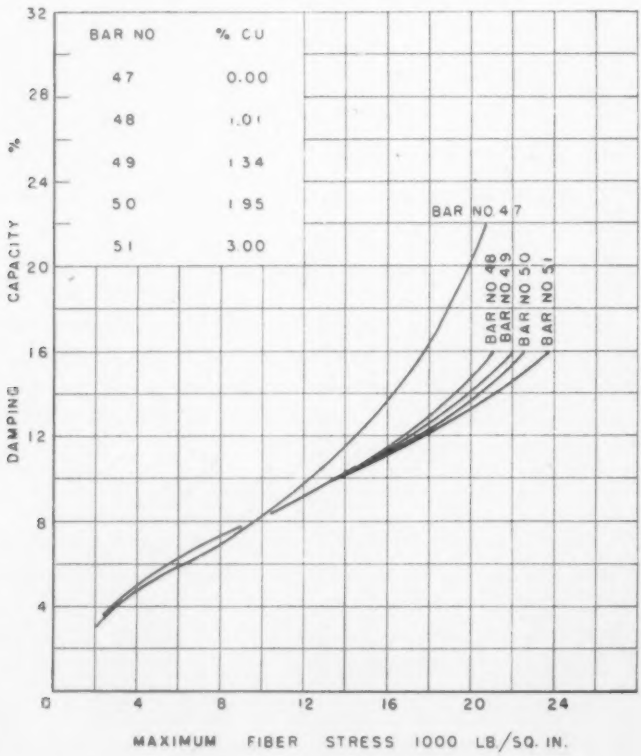


FIG. 6—DAMPING CAPACITIES FOR LOW-CARBON COPPER CAST IRONS.

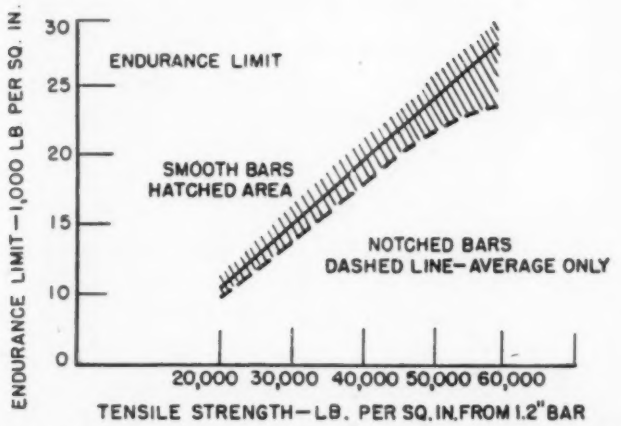


FIG. 7—COMPOSITE CURVE OF ENDURANCE DATA ON CAST IRONS SHOWING THE RELATION OF ENDURANCE LIMIT TO TENSILE STRENGTH FOR SMOOTH AND NOTCHED SPECIMENS.

notch, the notched bar endurance limit falling a few per cent below that of the unnotched bar, but the effect is scarcely evident in irons of 40,000 lb. per sq. in. tensile strength. This is brought out by the references cited. These data and others are plotted against tensile strengths as shown in Fig. 7.

Table 3

COPPER CAST IRONS USED IN THE DAMPING STUDIES AND A SUMMARY OF THEIR DAMPING CAPACITIES AT STRESSES EQUIVALENT TO 15 AND 35 PER CENT OF THE TENSILE STRENGTH

	*Chemical Composition**				*% Damping Capacity at Stresses Equal to*	
Bar No.	*T.C. %*	*Si. %*	*Cu. %*	*Tensile Strength 1.2-in. Section, lb. per sq. in.*	*15 Per Cent T.S.*	*35 Per Cent T.S.*
			High-Carbon Cast Irons			
4	3.37	1.00	0	40,500	9.9	23.4
5	3.36	1.07	1.00	45,500	10.5	19.6
6	3.32	1.09	1.72	49,000	10.6	19.5
12	3.36	1.09	2.09	49,000	10.1	19.7
13	3.39	1.08	3.01	51,500	11.0	19.7
			Medium-Carbon Cast Irons			
30	3.16	1.54	0	48,500	9.0	21.3
31	3.20	1.50	0.53	47,500	9.8	19.3
32	3.18	1.59	0.99	50,000	9.7	18.2
33	3.15	1.58	1.45	53,000	9.8	19.8
34	3.18	1.49	1.98	54,500	10.0	20.4
35	3.16	1.44	3.10	56,000	9.2	15.1
			Low-Carbon Cast Irons			
47	2.90	1.57	0	55,500	7.2	19.0
48	2.89	1.57	1.01	58,500	7.6	15.2
49	2.87	1.58	1.34	60,000	7.8	15.1
50	2.91	1.54	1.95	59,500	7.7	14.3
51	2.96	1.56	3.00	60,000	7.8	14.6

*Manganese, per cent..... 0.52-0.58
Sulphur, per cent..... 0.09-0.11
Phosphorus, per cent..... 0.21-0.23

EXPERIMENTAL DATA

Endurance Properties of Some Copper Cast Irons

21. The results of a series of fatigue tests on six lots of medium-carbon cast irons containing different amounts of copper are shown in Table 4.

Table 4

ENDURANCE LIMIT AND ENDURANCE RATIOS OF CAST IRON CONTAINING 3.15 PER CENT CARBON, 1.50 PER CENT SILICON, ALLOYED WITH COPPER

Bar No.	*C.* %	*Si.* %	*Cu.* %	*Tensile Strength, lb. per sq. in.* (*A*)	*Endurance Limit, lb. per sq.in.* (*B*)	*Endurance Ratio,* $\frac{(B)}{(A)}$
30	3.16	1.54	0	48,500	23,000	0.47
31	3.20	1.50	0.53	47,500	19,000	0.40
32	3.18	1.59	0.99	50,000	22,000	0.44
33	3.15	1.58	1.45	53,000	24,000	0.45
34	3.18	1.49	1.98	54,500	24,000	0.44
35	3.16	1.44	3.10	56,000	23,000	0.41

22. These tests were made with the standard R. R. Moore high-speed fatigue machines, operating at approximately 10,000 revolutions per minute. The specimens were of the standard type, machined from the 1.2-in. diameter test bar. The standard specimen is 0.270-in. in the smallest section and has a contour swept with a 4.993-in. radius. It is $3\frac{7}{16}$-in. long.

23. The endurance limit, as given in Table 4, was determined by testing six specimens of each iron at various loads. A typical SN curve is shown in Fig. 8. As shown in the tabulation, an increase in the copper content is accompanied by a slight decrease in the endurance ratio. This is typical of the high-strength alloyed cast irons.

THERMAL AND ELECTRICAL PROPERTIES OF SOME COPPER ALLOY CAST IRONS

24. There are frequent inquiries with regard to the effect of copper additions on the thermal conductivity and the electrical properties of gray cast irons. These inquiries are prompted by the anticipation that the addition of copper, with its high conductivity, may have a more decided effect on these properties of cast iron than

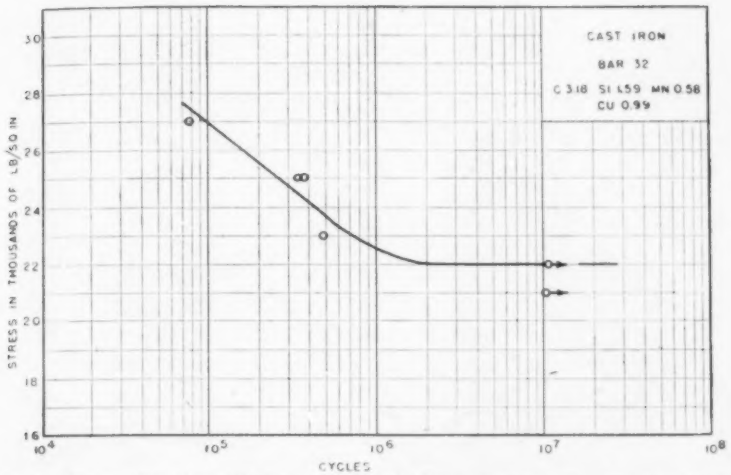


FIG. 8—TYPICAL SN (STRESS-NUMBER OF CYCLES) CURVE OBTAINED IN DETERMINING THE ENDURANCE LIMIT FOR CAST IRON.

the addition of other elements of lower conductivities. The available evidence indicates that copper, in the amounts used in the common engineering irons, has little effect on either the thermal or the electrical conductivity. It is believed that in general the effect of changes in the carbon and silicon contents and the microstructure of cast iron overshadows the effects of additions of normal amounts of alloying elements to the engineering irons.

Thermal Conductivity

25. The 1940 edition of the Cast Metals Handbook, page 437, states that the thermal conductivity of gray cast iron varies from 0.110 to 0.137 calories per square centimeter per second per degree Centigrade. These values depend upon the composition and the structure of the iron. As the temperature is increased, the value for thermal conductivity is lowered. Donaldson,[11] in a recent publication, has reported the results of an investigation of the thermal conductivities of high strength and alloyed cast irons. These results are shown in Table 5.

26. To supplement these data, the thermal conductivities of a series of medium carbon cast irons, containing from 0 to 3 per cent copper were determined. The method used was that developed by the National Bureau of Standards. It is described in Research Papers RP 668 and RP 669.[12] The method, in brief, consisted of heating one end of the specimen, measuring the temperature gradi-

Table 5

THERMAL CONDUCTIVITIES OF PLAIN AND ALLOY CAST IRONS AT 100 AND 400°C.

Bar No.	Composition T.C. %	Si. %	Mn. %	Ni. %	Cr. %	Alloying Element	K 100 deg. C.	K 400 deg. C.
1	3.16	1.48	0.97	...	...	...	0.122	0.108
2	3.25	1.91	0.97	...	...	...	0.110	0.103
3	3.32	1.52	2.43	...	...	...	0.118	0.101
4	3.16	1.56	0.94	0.75	...	...	0.108	0.101
5	3.17	1.40	0.97	...	0.39	...	0.131	0.114
6	3.19	1.45	0.99	...	...	V—0.124	0.122	0.103
7	3.02	1.89	0.76	...	...	W—0.475	0.118	0.105
8	3.20	1.56	0.72	...	...	...	0.121	0.108
9	3.18	1.58	0.69	...	...	Cu—1.58	0.112	0.101
10	3.11	2.26	0.89	...	...	...	0.111	0.101
11	3.12	2.31	0.89	...	0.54	Mo—0.77	0.119	0.109
12	2.61	2.46	0.45	...	...	...	0.110	0.100
13	2.56	2.20	0.63	...	...	Mo—0.58	0.118	0.108
14	2.80	2.51	0.68	1.71	0.54	...	0.101	0.092
15	3.10	2.51	3.11	1.00	...	...	0.106	0.097
16	3.41	1.03	0.65	1.49	0.54	...	0.116	0.106
17	2.41	1.80	0.62	13.70	3.37	Cu—6.41	0.081	0.075
18	2.70	0.96	0.58	...	0.95	Al—7.00	0.079	0.072
19	1.81	6.42	...	18.65	2.02	...	0.070	0.063

ent along the specimen and quantity of heat passing through it by means of a heat-flow meter, which is a standard metal of known conductivity in contact with the cold end of the specimen. The specimens were machined from standard 1.2-in. diameter transverse test bars. They measured 2.0 cm. (0.78 in.) in diameter and 15 cm. (5.85 in.) in length. The results obtained by this method are comparable to those obtained by Donaldson, who used a somewhat different method of measuring the thermal conductivity.

27. The experimental data are summarized in Table 6. The values for the thermal conductivities at 23, 100, 200, 300 and

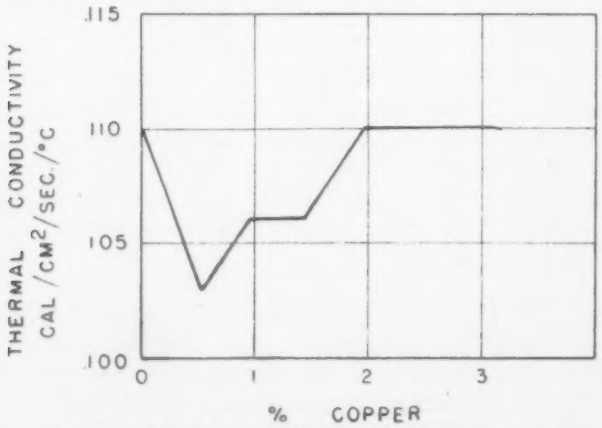


FIG. 9—THE EFFECT OF COPPER ON THE THERMAL CONDUCTIVITY OF A 3.15 PER CENT CARBON, 1.50 PER CENT SILICON CAST IRON AT 100°C. (212°F.).

400°C. (73, 212, 392, 572, and 752°F.), shown in Table 7, were obtained by interpolation of the experimental data. In Fig. 9, the thermal conductivities at 100°C. (212°F.) are plotted against copper content.

Table 6

THERMAL CONDUCTIVITY DATA ON SIX MEDIUM-CARBON, COPPER CAST IRONS

Bar No.	*Copper Content, Per Cent*	*Mean Temperature, °C.*	*Thermal Conductivity, Cal./cm.²/sec./°C.*
30	0	163.5	0.107
		242.6	0.103
		324.4	0.100
		407.9	0.099
31	0.53	159.5	0.102
		237.6	0.099
		317.0	0.098
		398.9	0.095
32	0.99	159.7	0.105
		237.1	0.102
		317.1	0.099
		398.7	0.098
33	1.45	167.4	0.103
		240.9	0.101
		316.9	0.098
		394.5	0.097
34	1.98	161.9 (1st test)	0.107
		235.9[1] (1st test)	0.097
		315.4[1] (1st test)	0.093
		395.9 (1st test)	0.092
		176.7 (2nd test)	0.106
		259.7[1] (2nd test)	0.096
		348.7[1] (2nd test)	0.093
		439.2 (2nd test)	0.093
		94.1 (3rd test)	0.109
		131.4[1] (3rd test)	0.102
		170.7[1] (3rd test)	0.099
		209.5 (3rd test)	0.103
35	3.10	165.4 (1st test)	0.106
		246.0 (1st test)	0.101
		329.3 (1st test)	0.101
		413.3 (1st test)	0.097
		97.3 (2nd test)	0.107
		138.3 (2nd test)	0.107
		179.6 (2nd test)	0.107
		221.0 (2nd test)	0.107

[1] Sectioning of the test specimen showed porosity in the regions where these values were obtained, hence the low values.

Table 7

THERMAL CONDUCTIVITY OF COPPER CAST IRONS AT VARIOUS TEMPERATURES

Bar No.	Copper Content, Per Cent	Thermal Conductivity in Cal./cm.²/sec./°C. 23°C.	100°C.	200°C.	300°C.	400°C.
30	0	0.112	0.110	0.106	0.103	0.099
31	0.53	0.105	0.103	0.100	0.098	0.095
32	0.99	0.108	0.106	0.103	0.100	0.098
33	1.45	0.108	0.106	0.103	0.099	0.096
34	1.98	0.114	0.110	0.104	0.099	0.093
35	3.10	0.112	0.110	0.105	0.102	0.098

28. The effect of copper additions on the conductivity was small indeed although the indication that copper in amounts of 2 to 3 per cent did not lower the conductivity may be characteristic.

Electrical Resistivity

29. The electrical resistivities of the same series of medium carbon irons which were used for the determination of thermal conductivities were measured. This property was determined on bars 0.75-in. (1.90 cm.) in diameter by 21-in. (53.40 cm.) long machined from the 1.2-in. transverse bars. The potentiometric method of measuring the resistance was used. The resistance was measured over a length of 40 cm. (15.7 in.) at a temperature of 23.5°C. (74.3°F.).

30. The experimental data are summarized in Table 8. These results are plotted against copper contents in Fig. 10. The resistivi-

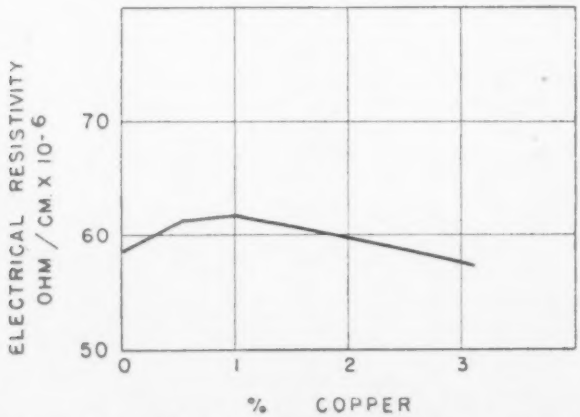


FIG. 10—EFFECT OF COPPER ON THE ELECTRICAL RESISTIVITY OF A 3.15 PER CENT CARBON, 1.50 PER CENT SILICON CAST IRON.

Table 8

ELECTRICAL RESISTIVITY OF COPPER CAST IRONS AT 23.5°C.

Bar No.	*Copper Content, Per Cent*	*Resistivity, Ohm/cm. x 10-6*
30	0	58.4
31	0.53	61.4
32	0.99	61.8
33	1.45	61.0
34	1.98	59.2
35*	3.10	57.4

*Specimen 35 was flawed at one end. To avoid the flaw the potential terminals were placed to cover good metal only.

ty of the iron increased slightly with the copper content up to 1 per cent and then decreased with further increases of copper. The resistivity of the copper iron, which contained 2.5 per cent copper, equalled that of the copper-free iron.

31. From a practical viewpoint, these results indicate that the effect of copper in amounts up to 3 per cent on the resistivity of cast irons is insignificant.

Appendix A

METHOD FOR COMPUTING DAMPING CAPACITY

The Foeppl-Pertz damping test puts a test piece in torsion. The stress-strain diagram, Fig. 11, illustrates the method of computation.

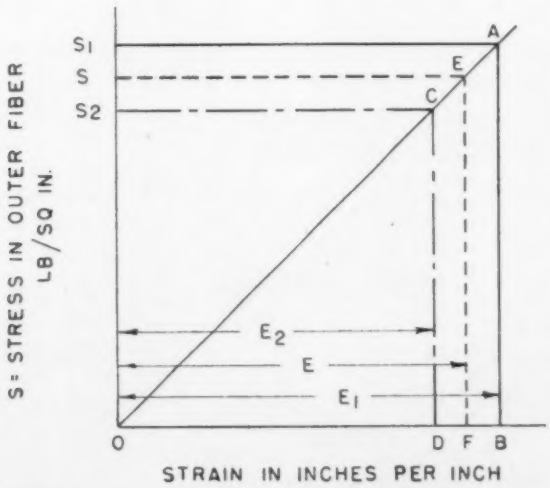


FIG. 11—STRESS-STRAIN DIAGRAM ILLUSTRATING METHOD OF CALCULATING DAMPING CAPACITY.

When the test piece is twisted to an amplitude e_1, it contains elastic energy represented by ½ the area *OAB*, because the stress varies from a maximum in the outer fibers of the specimen, represented by the ordinate *AB*, to zero at the point *O*. At the end of one vibration, the amplitude will be e_2 and the energy is represented by half the area *OCD*. The energy loss during the vibration is represented by the area ½ *DCAB*, The mean energy during the cycle is represented by half the area *OEF*.

The damping capacity is defined as the per cent energy loss per cycle. This is given by the expression:

$$\Psi = \text{per cent damping capacity} = \frac{\frac{Area\ DCAB}{2}}{\frac{Area\ OEF}{2}}$$

The area DCAB $= S\ (e_1 - e_2) = S\Delta e$ where
S is the mean stress per cycle.
The area $OEF = \frac{1}{2}\ S \times e$. Therefore,

$$\Psi = \text{per cent damping capacity} = \frac{S\Delta e}{\frac{1}{2}\,Se} = \frac{2\Delta e}{e}$$

The Foeppl-Pertz instrument is a device for measuring the quantites Δe and e. The machine uses a specimen of length l and diameter d. The twist in the sample is magnified by a pen at radius R.

A damping test record is shown in Fig. 12.

The damping capacity can be computed from the test record by the following procedure:

(1) Measure the amplitude a_1
(2) Measure the amplitude a_2

a_1 is related to e_1 of Fig. 11 by the equation,

$$e_1 = \frac{a_1}{2} \times \frac{d}{2Rl} = \frac{a_1 d}{4Rl}$$

$$e_2 = \frac{a_2 d}{4Rl}$$ Now

$$\Delta e = e_1 - e_2 = \frac{d}{4Rl}\,(a_1 - a_2)$$ and,

$$e = \frac{e_1 + e_2}{2} = \frac{d}{4Rl}\,\frac{(a_1 + a_2)}{(\ 2\ )}$$

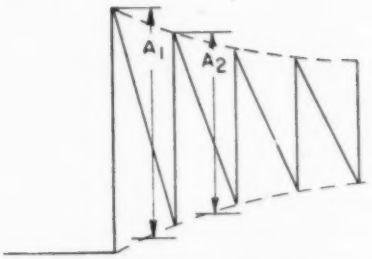


FIG. 12—DAMPING TEST RECORD.

Per cent damping capacity $\Psi = 100 \times \frac{2\Delta e}{e}$ therefore,

$$\Psi \text{ Per cent} = 100 \times \frac{\frac{2d}{4Re}(a_1 - a_2)}{\frac{d}{8Rl}(a_1 + a_2)}$$

$$= 100 \times \frac{2(a_1 - a_2)}{\frac{(a_1 + a_2)}{2}}.$$

S is the maximum stress between two vibrations.

$S = Ge$ when G is the shear modulus in lb. per sq. in.

In practice, it is seldom possible to measure the difference between successive vibrations accurately. Therefore the difference between two widely separated vibrations is measured and the average difference per vibration is then obtained by dividing by the number of vibrations between the two measured.

e then becomes $\frac{d}{4Rl}\frac{(a_1 - a_2)}{n}$ where n is the number of vibrations between a_1 and a_2.

Bibliography

1—SYMPOSIUM ON CAST IRON, A.F.A. and A.S.T.M., Chicago, 1933, 164 pp.

2—MacKenzie, J. T., *"Damping Capacity,"* PIG IRON ROUGH NOTES, Summer, pp. 9-12 (1939).

3—Robertson, L. S., *"Metallic Damping,"* METAL TREATMENT, vol. 3, Autumn, pp. 138-142, 150 (1937).

4—Moore, H. F., *"Crackless Plasticity, a New Property of Metals,"* IRON AGE, vol. 128, pp. 674-677, 721 (1931).

5—Foeppl, O., *"The Practical Importance of the Damping Capacity of Metals, Especially Steels,"* JOURNAL, IRON AND STEEL INSTITUTE, 84, pp. 393-455 (1936).

6—Von Heydekampf, G. P., *"Damping Capacity of Materials,"* PROCEEDINGS, A.S.T.M., vol. 31, pp. 157-175 (1931).

7—Smalley, O., *"Gear Castings with Special Reference to Cast Irons,"* FOUNDRY TRADE JOURNAL, vol. 57, pp. 62-65, 81-85 (1937).

8—Case, S. L., *"Damping Capacity and Aging of Steel,"* METAL PROGRESS, vol. 33, pp. 54-59 (1938).

9—*Report of Research Committee on Fatigue of Metals,* PROCEEDINGS, A.S.T.M., vol. 30, pp. 30-31, 259 (1930).

10—Kommers, J. B., *"The Static and Fatigue Properties of Some Cast Irons,"* PROCEEDINGS, A.S.T.M., vol. 28, pt. 2, p. 174 (1928); *"Fatigue Properties of Cast Iron,"* vol. 29, pt. 2, p. 100 (1929); *"The Effect of Under-Stressing on Cast Iron and Open Hearth Iron,"* vol. 30, pt. 2, p. 368 (1930).

11—Donaldson, J. W., *"The Thermal Conductivity of High-Duty and Alloy Cast Irons,"* FOUNDRY TRADE JOURNAL, vol. 60, June 15, 1939, pp. 513-515.

12—van Dusen, M. S. and Shelton, S. M., *"Apparatus for Measuring Thermal Conductivity of Metals up to 600°C.,"* BUREAU OF STANDARDS JOURNAL OF RESEARCH, vol. 12, pp. 429-440 (1934).

Shelton, S. M., *"Thermal Conductivity of Some Irons and Steels over the Temperature Range 100 to 500°C.,"* BUREAU OF STANDARDS JOURNAL OF RESEARCH, vol. 12, pp. 441-450 (1934).

13—Anon., *"A New Method of Determining Damping Coefficients,"* AUTOMOTIVE INDUSTRIES, vol. 80, March 1, 1940, pp. 252-255, 263.

14—Geiger, J., *"Damping Capacity of Cast Iron with Special Reference to Cast Crankshafts,"* DIE GIESSEREI, Jan. 12, 1940, pp. 1-9.

DISCUSSION

Presiding: H. BORNSTEIN, Deere & Co., Moline, Ill.

E. K. SMITH[1]: What is the limit of solubility of copper in ordinary cast iron without separation of metallic copper?

DR. LORIG: The amount of copper held in solution depends primarily on two things, the silicon content and the carbon content. In some high-carbon irons, we have noticed a separation of copper at about 4.5 per cent, but I have seen some high silicon irons that ran up to almost 20 per cent copper with no separation whatever.

MEMBER: Did the authors notice any effects as far as the corrosion resistance of these materials is concerned? Are these effects of copper maintained through the higher silicon ranges of 2.50 or 2.75 per cent silicon, with reference to corrosion, as well as these other properties?

DR. LORIG: We have not made any corrosion tests on the cast iron. Corrosion resistance is a rather indefinite property to determine since it depends so much on the materials that are being used and the corrosive media in which they are being tested as to the results obtained.

MEMBER: I understand as far as the Southwest is concerned, they are using a lot of cooper-bearing cast iron. I was wondering if it was because of its corrosion resistance or whether it was due to some other physical property of this particular metal.

DR. LORIG: I think it is primarily due to its added corrosion resistance, obtained through the copper, that the copper-bearing cast irons are being used in that area. Some of the solutions with which the cast iron is in contact probably contain sulphuric acid and copper is especially good in adding corrosion resistance to iron exposed to solutions of that kind.

MEMBER: What effect has the copper on the wearability of cast iron?

DR. LORIG: I have seen very little information which would bear out whether or not copper influences the wear resistance. The microstructure is one of many factors that has a tremendous effect on the wear resistance of iron. If copper tends to make the iron normal in structure, that is, if the copper addition changes the structure from one normally containing graphite in dendritic pattern and containing ferrite to one with flake graphite and a fully pearlitic matrix—changes which are quite possible to obtain—I think it probably would have a very decided effect on improving the wear resistance.

[1] Metallurgist, Electro Metallurgical Co., Chicago, Ill.

E. K. SMITH: I would agree with Dr. Lorig that the microstructure has quite an effect and that any alloy that will tend to give a preferred microstructure will increase the resistance to wear, for instance, copper, nickel, chromium or molybdenum or unalloyed irons that have preferred structure.

Dr. Lorig, will the copper eliminate ferrite?

DR. LORIG: It has a tendency to do so if added to the ladle. Like many other additions, it has an effect upon the iron if added late, just like steel and many other ladle additions will tend to give a more or less normal structure if added late.

T. E. EAGAN[2]: I want to add something about the addition of copper to resist wear in diesel engines. Up to one per cent, it does not increase the resistance to wear, but we believe gives just the opposite result. After a year and one-half of investigation on wear resistance in diesel engine liners, we have found that copper is a very poor addition to put into a liner to resist wear.

CHAIRMAN BORNSTEIN: Would you mind telling us what the base composition of that metal was?

MR. EAGAN: It was around 2.70 to 3.10 per cent total carbon, 1.70 per cent silicon, and an addition of 1 per cent copper.

A. L. BOEGEHOLD[3]: In Mr. Eagan's case, copper had a deleterious effect, but I can cite cases where the effect would be the reverse. With a structure that is unbalanced to the extent that there is a certain amount of brittle carbides in the structure, copper can be put in to counteract that effect and bring it back to where it should be. In that case, there will probably be an increase in wear resistance. I say "probably." As a matter of fact, we have some results of tests on a lubricated wear test machine that indicate that is the case.

G. P. PHILLIPS[4]: I might add that the wear tests we have been running on hardened diesel sleeves for about two years, copper-chrome hardened sleeves, have shown very good results on all wear tests. I just mention that to go along with the statement Mr. Eagan made about his bad results.

CHAIRMAN BORNSTEIN: A lot of experiments that we have made on additions of various alloys and combinations of alloys to cylinder blocks indicates that the addition of copper and chromium to cast iron has increased the wear resistance and has improved the microstructure.

---

[2] Chief Metallurgist, Cooper Bessemer Corp., Grove City, Pa.

[3] Metallurgist, General Motors Corp., Detroit, Mich.

[4] Metallurgist, International Harvester Co., Chicago, Ill.